THE SNELLIUS-EXPEDITION

IN THE EASTERN PART OF THE NETHERLANDS EAST-INDIES 1929-1930

UNDER LEADERSHIP OF

P. M. VAN RIEL

DIRECTOR OF THE AMSTERDAM BRANCH OFFICE OF THE
NETHERLANDS METEOROLOGICAL INSTITUTE

V

VOLUME II

OCEANOGRAPHIC RESULTS

PART I

METHODS AND INSTRUMENTS

CHAPTER I

THE OCEANOGRAPHIC INSTRUMENTS AND THE ACCURACY OF THE TEMPERATURE OBSERVATIONS

BY

H. C. HAMAKER

CHAPTER II

THE DETERMINATION OF CHLORINE AND OXYGEN CONTENT

BY

H. J. HARDON

1941

TO BE OBTAINED OF THE PRINTERS AND PUBLISHERS

E. J. BRILL - LEIDEN

SNELLIUS-EXPEDITIE

WETENSCHAPPELIJKE UITKOMSTEN DER SNELLIUS-EXPEDITIE

ONDER LEIDING VAN

P. M. VAN RIEL

DIRECTEUR VAN DE FILIAALINRICHTING VAN HET
NEDERLANDSCH METEOROLOGISCH INSTITUUT TE AMSTERDAM

VERZAMELD IN HET OOSTELIJKE GEDEELTE VAN NEDERLANDSCH OOST-INDIË
AAN BOORD VAN H. M. WILLEBRORD SNELLIUS

ONDER COMMANDO VAN

F. PINKE

LUITENANT TER ZEE DER 1e KLASSE

1929–1930

UITGEGEVEN DOOR DE MAATSCHAPPIJ TER BEVORDERING VAN HET
NATUURKUNDIG ONDERZOEK DER NEDERLANDSCHE KOLONIËN EN
HET NEDERLANDSCH AARDRIJKSKUNDIG GENOOTSCHAP

GEDRUKT DOOR EN TE VERKRIJGEN BIJ
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CHAPTER I

THE OCEANOGRAPHIC INSTRUMENTS AND THE ACCURACY OF THE TEMPERATURE OBSERVATIONS

§ 1. INTRODUCTION

Apart from the inconvenience of a tropical temperature the conditions in the region visited by the Snellius expedition were exceptionally favourable for oceanographic research. Of about 3000 true wind observations the percentage lying below a given value has been plotted in fig. 1; in 90% of the cases the velocity was less than 7 M/sec. (4 Beaufort) and a windvelocity of 12 M/sec. was recorded on a few occasions only. Needless to say that the sea was correspondingly smooth.

Under such conditions work at sea is comparatively easy. The strain on the machinery is reduced to a minimum and there is no damage to be feared from the tossing of the ship. Consequently our loss of instruments was very small and repeatedly experiments were made which could not be thought of under less favourable circumstances. In reading the following report this should be born in mind.

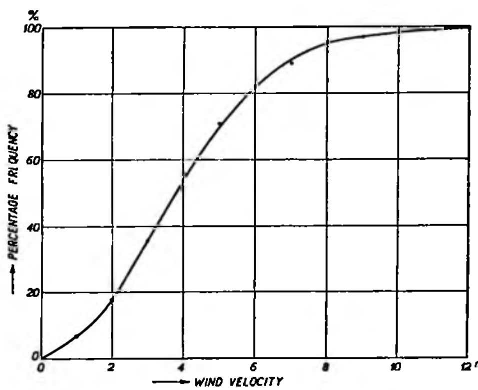

Fig. 1. Percentage of wind velocity observations lying below a given value.

The search for accurate methods and instruments initiated by Helland-Hansen and Nansen [1]) about thirty years ago has in many respects been completed by the painstaking researches of Merz and his collaborators while preparing the Meteor Expedition. Most of the instruments used on the Snellius were of the same pattern as those adopted by the Meteor and our methods for recording the observations were also for the greater part copied from that famous expedition. As a detailed discription of these apparatuses and their use has been given in the Meteor Reports [2]) we need not consider them here in all particulars. We will discuss our results only in so far as they differ from those of the German Expedition or furnish supplementary evidence on points where such evidence seems of value. The accuracy of our observations, being of essential importance in the interpretation of our material, will be discussed in detail.

In the up-keep of our instruments we were effectively assisted by an instrumentmaker of the Royal Dutch Navy especially detached on board Snellius for that purpose. The tropical climate necessitated an almost daily supervision of our instruments and without an extra man for that job it would hardly have been possible to keep them in good working condition throuh gout the expedition.

In carrying out the observations we enjoyed the help of several members of the crew. We still retain the most pleasant remembrances of the daily cooperation and we wish to express our gratitude for their able assistance.

§ 2. THE GREAT WINCHES FOR SERIAL OBSERVATIONS

One of the chief implements in deep sea research is a large amount of wire and a machine with which to handle the wire. The machines used for this purpose were of the same pattern as those of

[1]) B. Helland-Hansen and F. Nansen. The Norwegian Sea, Christiania, 1909.
[2]) Vol. IV. Part. I.

the Meteor expedition though slightly altered to fit the space available. For a detailed description we refer to the Meteor reports [1]).

We had with us:

1. Two electrically driven oceanographic winches complete with meter-wheels and the necessary spare parts. (Mohr and Federhaff, Mannheim). Of the spare parts some contact points for the electric switches and a brake strap were all that were used.

2*a*. 2 × 9000 M. steel wire, 4 mm in diameter. Breaking load 1500 KG.

2*b*. 2 × 8000 M. aluminium bronze wire, 4 mm in diameter. Breaking load 800 KG. Both wires were manufactured by Felten and Guilleaume Carlswerk A. G. Köln-Mülheim. A complete report on the properties of these wires has been given in the Meteor reports [2]). 9000 M steel wire and 8000 M bronze wire were on the winches; the rest was kept in reserve.

3. 2 extra dials fixed on the winches and connected by Bowden cable to the main meter wheels. The purpose of this arrangement will be explained below.

4. A dynamometer to measure the tension on the wire. Made by Marx and Berndt. Berlin. See Meteor reports Vol. IV Part I p. 194.

5. A spare meter-wheel. (Marx and Berndt).

A sketch of the situation on board is given in figs. 2 and 3. From the reel R the wire goes via a roller S to the meter-wheel M and thence down into the sea. The meter wheel is fixed at the end of a spar SP $\pm$ 3 M long which can be veered away by means of a small hand winch HW on the upper deck so as to keep the wire from off the vessel. When the wire is drawn in the mechanism T ensures a uniform distribution of the wire over the drum.

The reel is driven by a 14 h.p. electromotor EM via two tooth gears TG which cut down the velocity of rotation in the ratio 1 : 20. As soon as the current is switched off a magnetic brake B comes into action stopping the motor almost immediately. This prevents the motor from running on by inertia and the wire from being drawn into the sea by its own weight. When the motor is started the brake B is automatically released.

Once a 100 M of wire have been paid out the motor is no longer needed, the weight of the wire and the instruments attached to it being heavy enough to turn the reel. To this end the reel is disconnected from the motor by means of the brake band coupling C which is manipulated by the handle H. This arrangement serves not only as a coupling but also as a brake to regulate the speed with which the wire is veered away. Both the magnetic brake B and the coupling C proved very convenient in practice. PL is a small platform from which the instruments were fixed to the wire.

The machines were excellent and functioned without a hitch during the 13 months we were at sea. As mentioned earlier but a few of the spare parts were used.

The situation on board was such that the person attending the switch could not see the dial of the meter-wheel (see fig. 3). This inconvenience was compensated for by a second dial connected by Bowden cable to the axis of the main meter-wheel and mounted on top of the reel near the switch as can be seen from Plate I Fig. 1.

Our two winches were mounted on the lower deck, one to starboard and one to port about 15 M from the bow of the ship (compare fig. 2 p. 54 in Vol. I of these reports). The starboard winch was wound with aluminium bronze wire and was used as a rule for depths not exceeding 4000 M. At greater depths we preferred the port winch which was fitted with steel wire. Corrosion was prevented by rubbing the steel wire on the reel with linseed oil while heaving in, a measure repeated at every station which proved entirely effective. The linseed oil formed a protecting crust on the wire and no traces of rust could ever be detected. Probably it is not necessary to repeat the treatment with linseed oil as often as we did; on the Meteor expedition a coating with cylinder oil once in 4 to 6 weeks was found sufficient. Since it is easy to keep the steel wire in good condition we readily agree with Böhnecke that this wire being twice as strong and $^1/_3$ the price may be used with advantage rather than a bronze wire.

That breaking of the wires never occurred must largely be attributed to the favourable wheather

[1]) Vol. IV. Part. I. p. 178 ff.
[2]) Vol. IV. Part. I. p. 186 ff.

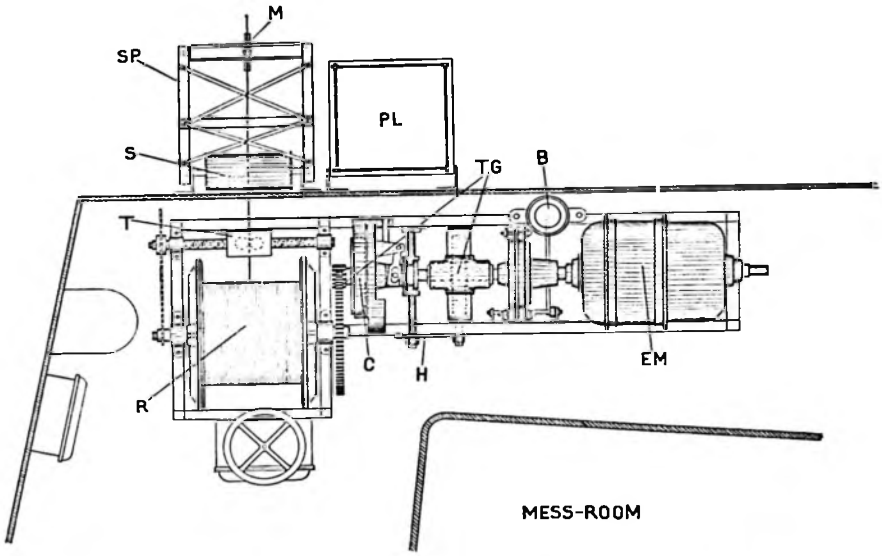

Fig. 2. Horizontal plan of the great winch to starboard.

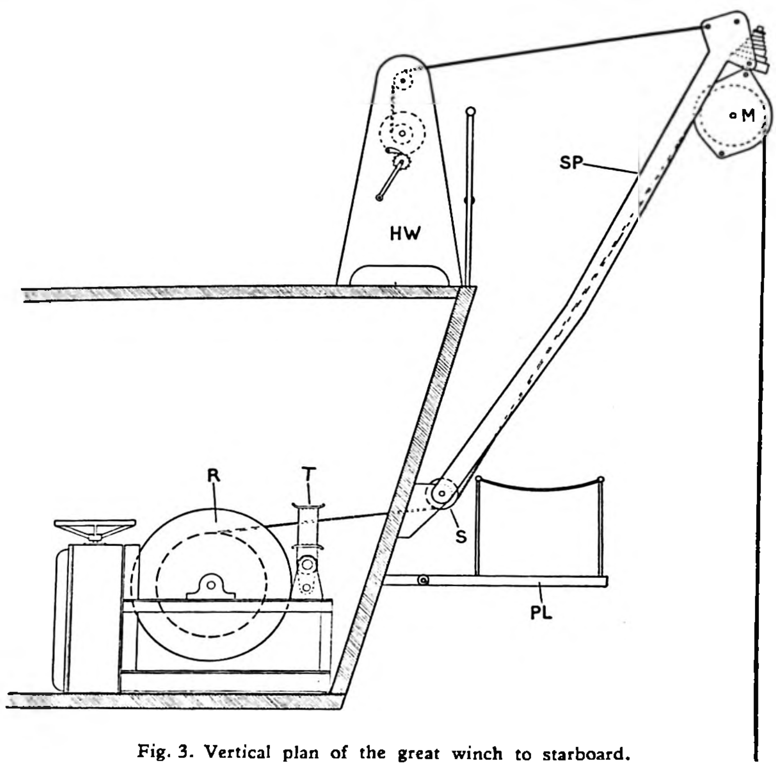

Fig. 3. Vertical plan of the great winch to starboard.

EM = Electromotor.
B = Magnetic brake.
H = Handle which controls C.
R = Reel with wire.
S = Roller.
M = Meter-wheel.
PL = Platform from which the instruments were fixed to the wire.
TG = Tooth gears.
C = Brake band coupling.
T = Wire distributor.
SP = Spar.
HW = Handwinch on upper deck.

conditions; once some strands of the bronze wire snapped but this was detected in time to prevent a loss of instruments. To measure the strain on the wires we used a dynamometer as described in the Meteor reports. The calm seas however rendered a regular check of this kind superfluous; the tension on the wire never reached a value of half the breaking load.

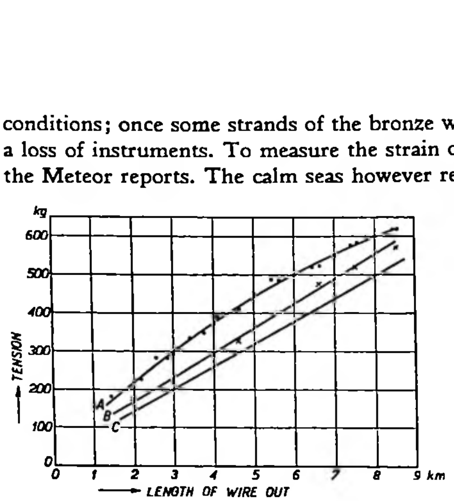

Fig. 4. Tension on the wire plotted against the length of wire out.

A. Hauling in at full speed.
B. With motor stopped.
C. Weight of wire and instruments in water.

At station 264 on a very calm day when water samples were taken down to 8500 M with the port winch some observations were made to illustrate the general performance of the machinery. The dynamometer was read at intervals both while hauling in at full speed and when the motor was stopped; the result is represented by curves *A* and *B* respectively in fig. 4. Curve *C* in the same figure gives the weight of the wire and waterbottles calculated from their weight in air. All data have been plotted against the lengh of wire still out.

We should expect curves *B* and *C* tot coincide, so that the difference which is actually observed must be due to systematic errors in the indications of the dynamometer. Whether these existed from the beginning or are the result of wearing out we do not know. The difference between the curves *A* and *B* is due to the friction of the wire and the instruments in the water.

By observing the time required to haul in 100 M of wire the velocity of hauling in was found (fig. 5).

Finally the energy consumed by the motor per second (voltage × current) and the work performed on the wire while hauling in (velocity × tension) both expressed in KGM/sec have been

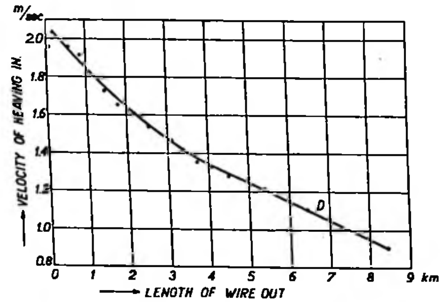

Fig. 5. Verlocity of hauling in at full speed against length of wire out.

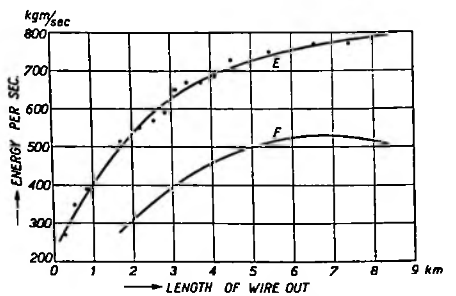

Fig. 6. Energy per second consumed by the motor (curve *E*) and performed on the wire (curve *F*).

plotted in fig 6, curves *E* and *F*; in making the necessary computations the readings of the dynamometer were corrected for the systematic errors referred to above.

Some observations on the diameters of the meter-wheels should also be recorded here; they have been entered in table 1.

TABLE 1. Diameters of the meter wheels.

Date	Diameter in mm		Length of wire that passed the wheels in KM	
	Port	Starboard	Port	Starboard
July 1929	314.5	314.5		
May 1930.	312.6	314.0	227	456
November 1930	311.8	314.0	196	156

As might be expected the changes in diameter at starboard (bronze wire and depth to 4000 M) are less than those at port (steel wire and great depths). In the last case the meter wheel seems to have worn off mostly during the first half of the expedition. This however is not perfectly certain; for the diameters for July 1929 are those taken from the constructional drawings, which were not checked by separate measurement. It is not inconceivable that the actual diameters were somewhat different.

Since the depths of the serial observations were systematically determined with unprotected reversing thermometers the changes in the diameter of the meter-wheels will not affect the reliability of our depths of observation. On the other hand if the port wheel has worn off 2.7 mm as indicated by table 1 this should have brought about a systematic difference between the thermometric depth and the length of wire gradually increasing in the course of the expedition to about 0,9% of the depth. Owing to the larger and irregular differences resulting from the varying slope of the wire, however, it has been impossible to trace this effect in our observations.

§ 3. WATER BOTTLES

A. Inventary.

We had on board:

1. 40 Nansen reversing water bottles of $1^1/_4$ L content each with a removable frame for two reversing thermometers and with a messenger; 16 of these instruments were obtained from Bergen Nautik A/G in Bergen, Norway, whereas the 24 remaining water bottles were manufactured by Marx and Berndt in Berlin.
2. 18 spare thermometer frames to the water bottles. It was very convenient to have these.
3. 43 spare messengers; this was far too much since no messengers were lost and they did not get out of order either. At the conclusion of our work the officers and the members of the scientific staff were presented with one of the superfluous messengers as souvenir.
4. An ample number of spare parts to the water bottles and messengers, such as springs, screws, etc. The parts of the water bottle that are hit by the messenger are apt to be damaged in the long run; a reserve of these is specially useful.
5. 3 large 4 L water bottles as used by the Meteor [1] but without a glass cylinder. These instruments were rarely used for reasons that will be more fully explained below.

For taking bottom observations together with the wire soundings we had:

6. 6 reversing thermometer frames with propeller release made by Bergen Nautik A/G, Bergen, Norway.
7. 12 Sigsbee water bottles; 6 of these from Marx and Berndt in Berlin and the other 6 from Carl Seemann in Hamburg.
8. 6 Ekman reversing water bottles with propeller as used on board of the Meteor [2]. (Marx and Berndt).

B. The Nansen reversing water bottles.

The Nansen reversing water bottle now in general use for collecting water samples from below the surface consists essentially of a tin plated brass cylinder fitted with large stop cocks at both ends. When going down the lower end of the water bottle is tightly screwed to the wire while the upper end is fixed by a special releasing mechanism; both stop cocks are open so that the water flows freely through the bottle during its downward passage.

When the bottle has reached the depth from which we intend to take a water sample a so called messenger is sent down along the wire which on striking the releasing mechanism releases the upper end. The bottle now turns over and by the movement both stop cocks are closed. At the same time two reversing thermometers fixed to the bottle in a separate frame register the temperature at the depth at which the bottle is reversed. Meanwhile the messenger drops on the fixing catch at the

[1]) Meteor Reports Vol. IV. Part. I. p. 27.
[2]) Meteor Reports Vol. IV. Part. I. p. 26.

lower end where it releases another messenger by which water bottles fixed lower down on the wire can be set going; in this way it is possible to use a number of water bottles at different depths on the same line.

When hove on deck again the water samples trapped inside the bottles can be tapped off by a small cock made for that purpose.

A photograph of the water bottle is reproduced in fig. 2 Plate 1; a more detailed description with a constructional drawing will be found in the Meteor Reports [1]).

As mentioned in the inventary we bought our Nansen reversing water bottles partly from Bergen Nautik A.G., Bergen, Norway, and partly from Marx and Berndt in Berlin. The principal measures of the two types have been compared with each other in table 2. The German instrument

TABLE 2. Some measures of German and Norwegian water bottles.

	German	Norwegian
Content.	1350 cc	1350 cc
Total weight with two reversing thermometers.	5 KG	4 KG
Total length.	70 cm	63 cm
Inner diameter of cylinder	5.5 cm	5.7 cm
Surface of openings in the stop cocks	5.6 cm²	4.6 cm²
$\frac{\text{Openings of stop cocks}}{\text{Cross section of cylinder}}$	0.25	0.18

has larger openings in the stop cocks so as to ensure a more efficient flow of water through the bottle. However, we do not think this difference of any significance. On one occasion a German and a Norwegian water bottle only about one meter apart were let down to that depth where the salinity gradient was greatest (75 M) and were made to close immediately after arriving there. Between the two water samples brought up in this way a difference in salinity could not be observed so that the flow through the bottles must have been equally effective. In the actual observations the difference if any must be still less as the instruments were always left at the intended depth for at least ten minutes before they were closed and all that time they were slowly pumping up and down with the movement of the ship.

Apart from the difference in the stop cocks the German water bottle is also of a more robust construction and consequently heavier. On the other hand the Norwegian instruments were considerably cheaper.

On the whole both instruments served our purposes equally well so that it is difficult to say whether the one is preferable to the other. Possibly, however, under less favourable weather the heavy construction of Marx and Berndt will have its advantages.

To keep the instruments in functioning order they were continually inspected; at intervals they were rinsed with fresh water and three or four times during the expedition they were taken to pieces and thoroughly cleaned. In his report Bohnecke [2]) mentions that the stop cocks did not always close tightly enough even though they were most carefully looked after. This trouble we never experienced. Upon a systematic inspection of our observations about 50 salinity determinations have been set aside as obviously erroneous; only in one single case, however, was the error in salinity coincident with an error in the oxygen content as we should expect if they were due to a leakage in the stop cocks.

It should finally be noted that at our request the messengers were rounded off at their lower end as shown in fig. 7A. A flat bottomed messenger (fig. 7B) when striking the releasing mechanism will cause a greater strain on the axle b and is more likely in the long run to cause unnecessary damage.

In one respect the water bottles were perhaps not as perfect as could be desired. The oxygen content in the deep sea basins of the East Indian Archipelago is remarkably constant as is illustrated in fig. 8. Between 2000 and 5000 M the variation is hardly more than 0.1 cc 0_2/L; in the open ocean the differences are much more pronounced. Consequently if we wish to draw conclusions concerning the water movement in the deep sea basins from the oxygen observations we must be very certain

[1]) Vol. IV. Part. I. p. 21 ff.
[2]) Meteor Reports. Vol. IV. Part. I. p. 25.

that absorption of oxygen by the water bottles is vanishingly small. Knudsen [1]) has demonstrated that metal parts absorb oxygen from sea water at a considerable rate; for instance the oxygen content of a water sample in a vessel of tinned brass decreased from 4.65 to 2.64 cc 0_2/L in 30 hours. Since it takes between one and two hours to bring a water sample of great depth to the surface variations of the order of 0.1 cc 0_2/L may be expected as a result of absorbtion by the water bottles, and it is not very likely that the different instruments absorbed oxygen at exactly the same rate. Hence in interpreting such small changes in oxygen content as registered in fig. 8 we must be very careful.

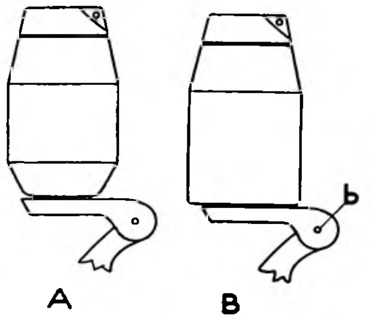

Fig. 7. Messengers for the water bottles. A rounded off to prevent undue damage. B original shape.

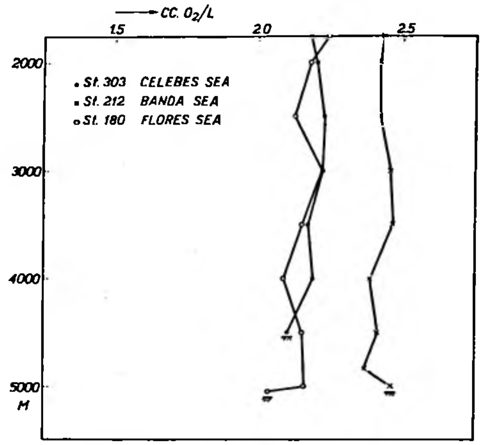

Fig. 8. Illustrating the constancy of oxygen content in the deep sea basins of the archipelago.

This has been further corroberated by observations carried out by Dr. Liebert at den Helder with some water bottles which we brought back to Holland after the expedition. His results are recorded in table 3.

TABLE 3. Absorbtion of oxygen by the water bottles according to experiments by Dr. F. Liebert, den Helder.

Exp. 1.	Oxygen content ccO_2/L
Water bottles filled with sea water with σ_0 = 22,1 and Temp. = 7° C.	10,86
After being kept at 7° C for 1½ hour in	
Nansen reversing water bottle (Norwegian) . . .	10,78
Nansen reversing water bottle (German)	10,87
Bottom water bottle	10,94
Sigsbee water bottle	10,71
Exp. 2	
Water bottles filled with sea water with σ_0 = 29,2 and T = 16,2° C.	8,20
After being kept 1 hour at 16° C in	
Nansen reversing water bottle (Norwegian) . . .	8,14
Nansen reversing water bottle (German)	8,02
Bottom water bottle	7,75
Sigsbee water bottle	7,96

[1]) M. Knudsen. Publ. de Circ. 77. 1923.

At 7° C the absorbtion is small but at 16° C a decrease in oxygen content of 0,06 and 0,18 cc O_2/L in one hour were actually observed with the Nansen reversing water bottles so that errors of that order of magnitude can not be excluded. The bottom water bottles show a considerably larger absorbtion; the errors caused by these instruments will be more fully discussed below.

C. The 4 Liter Water Bottles.

To collect large water samples of high chemical purity the Meteor [1]) constructed a water bottle of 4 L content in which the water sample is trapped between rubber sheaves in a glass cylinder so that contact with metal parts is completely precluded. To take water samples large enough for zoological analysis we adopted the same instrument only without a glass cylinder, but with an ordinary tin plated metal cylinder. The water samples collected with this apparatus were not chemically different from those obtained with the reversing water bottles, whereas the 4 L bottle was very heavy and not easy to handle. Therefore two or three reversing water bottles close together would serve our aims just as well and as they were more convenient in practice the 4 L water bottles were not used very often.

D. Bottom Water Bottles and Bottom Observations.

On board Meteor the Sigsbee water bottles used to take water samples near the bottom with the wire sounding were found unreliable. To remedy this Marx and Berndt constructed a water sampler [2]) similar to Knudsens modification of Ekmans [3]) reversing water bottle but operated by a propeller. This instrument which we used a good deal will be designated the ,,bottom water bottle''. A photograph is shown in Plate II fig. 6.

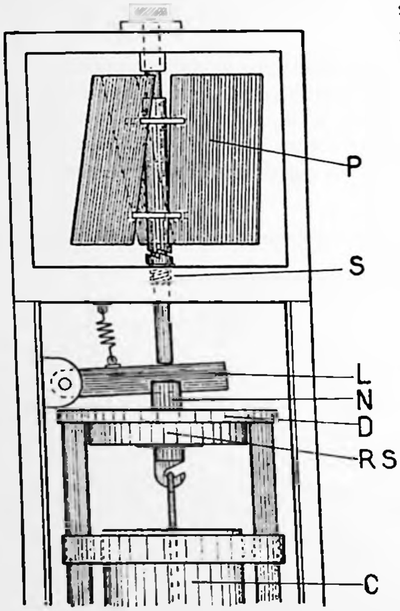

Fig. 9. Releasing mechanism of the bottom water bottle. RS = Rubber sheave; C = Tinplated brass cylinder in which the water sample is trapped. The other symbols are explained in the text.

The releasing mechanism is illustrated by the sketch in fig. 9. When going down the propeller P is free to rotate at will but when drawn up again P turning the other way catches and unscrews the screw S. Thereby the lever L is lifted and after about one revolution of the propeller the stud N on the lid D is free to pass underneath L. By the action of a strong spring the bottle swings round and closes while simultaneously the temperature is recorded by a reversing thermometer. The mechanism has been described in detail by Knudsen. The content of these instruments was ± 800 cm^3.

When sounding the water bottle was screwed to a piece of 4 mm bronze cable 1 M long which was fixed to the end of the piano wire via a swivel. Underneath this came 30 M hempen rope with the sounding tube, so that if the sounding machine stopped properly the water bottle would be about 30 M from the bottom.

At the outset the bottom water bottles of which we had six with us were almost exclusively used for taking bottom observations. Later on, however, we decided to take larger water samples from near the bottom and for this purpose the bottom water bottle was fitted with a device which drops a messenger at the moment the bottle reverses; the piece of bronze wire was made longer so as to take a Nansen reversing water bottle underneath the bottom water bottle. These two instruments were than used together; since the sea was usually very calm we did not fear increasing the risk of loosing our instruments by this alteration. In fig. 5 of Plate I the two water bottles will be seen just emerging from the sea.

[1]) Meteor Reports. Vol. IV. Part. I. p. 27.
[2]) Meteor Reports. Vol. IV. Part. I. p. 29.
[3]) V. W. Ekman. Publ. de Circ. 23, 1905. M. Knudsen. de Publ. Circ. 77, 1923.

When at station 272 the last but one of the bottom water bottles was lost we preferred to preserve the one remaining instrument which again necessitated a slight change in our method of observation. Amongst our instruments we had six propeller operated reversing thermometer frames bought from Bergen Nautik A.G. in Norway and these were now altered so as to drop a messenger when reversing as illustrated in fig. 10 and used in combination with a Nansen water bottle.

This last method proved the most satisfactory as is illustrated by the following data

	Bottom water bottles.	Reversing frame
Times used	215	82
Erroneous observations	32 = 19%	10 = 12%

Erroneous observations are those of which the temperature recorded could not possibly be made to fit the depth-temperature curve resulting from the serial observations.

That the reversing frames were the most reliable is easily understood. The sounding wire consisted of several pieces the joints between which had to be carefully inspected at every station to prevent an undue loss of instruments. Sometimes we even had to stop the sounding machine for a while in order to repair one of the joints and all that time the bottom instruments were slowly moving up and down with the rolling of the vessel. Since the propeller of the bottom water bottle was equipped with a freewheel and only one revolution was sufficient to set the bottle free this up and down movement was practically certain to spoil the observations by closing the bottle at a wrong depth. The reversing frame having no freewheel and being operated only after several revolutions of its propeller was less liable to this error. On the other hand the bottom water bottle has of course the advantage of closing more promptly when the sounding wire is drawn in again. By experiments at the surface we found that the bottom water bottle closed after travelling 5 meters whereas the reversing frame took 15 meters. However, we do not think this difference of great importance. In our opinion the setting of the bottom water bottle was somewhat too critical.

More closely to investigate the water layers near the bottom we have sometimes used three water bottles respectively 30, 60, and 90 meters above the sounding tube and fixed to a 60 meters piece of bronze cable at the end of the sounding wire. To start with we used Sigsbee water bottles in these experiments but later on we employed a bottom water bottle or reversing frame in combination with reversing water bottles.

In all experiments described so far the depth of observation depending on the proper action of a propeller is to some extent uncertain. In some special experiments, this disadvantage was avoided by using the port winch with 4 mm steel cable instead of the Lucas sounding machine. In calm weather and with a weight of 60 KG at the end of the wire it was possible to sound the bottom accurately to within a single meter using the dynamometer as indicator. With reversing water bottles operated by a messenger water samples could be collected only 5 or 10 M above the bottom without any risk. In later experiments of this kind the heavy 4 M sounding tube [1] was used at the end of the wire so that bottom samples of great length were brought on deck with the water samples.

From Dr. Liebert's observations recorded on page 7 it is seen that the bottom water bottles absorbed oxygen from the enclosed water sample to a marked degree. To judge from our data this has caused serious errors in our bottom observations during the first part of the expedition. The apparent errors in O_2 content are ac-

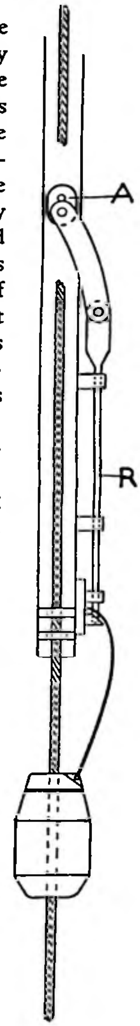

Fig. 10. Mechanism by which a propeller operated thermometer frame was made to drop a messenger when reversing. A is the axle of the frame; when the frame swings round the rod R is lifted.

[1] Ph. H. Kuenen. Ann. d. Hydrogr. u. Mar. Meteor. 1932. p. 93.

companied by marked discrepancies in P_h which may be explained by an analogous absorbtion of CO_2. Deviations in O_2 content and P_h which are probably due to errors are illustrated in fig. 11; discrepancies of this kind which were frequently observed during the first months of our work compietely disappeared after we started using the reversing water bottle for the bottom observations (compare for instance fig. 8). This renders it probable that they must be ascribed to absorption by the bottom water bottle. It must be noted, however, that after a careful analysis of our bottom observations Mr. v. Riel has come to the conclusion that it is not excluded that such deviations

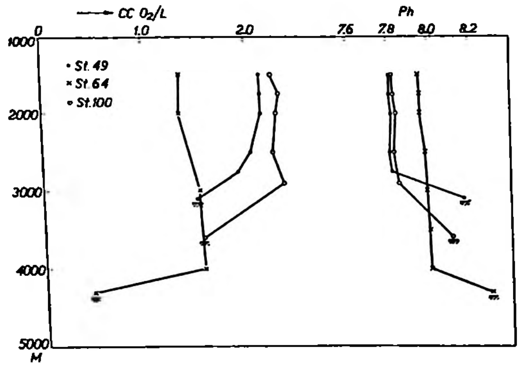

Fig. 11. Showing deviations of O_2 content and P_h on the bottom as observed during the first months of the expedition.

as shown in fig. 11 represent a real feature of the oceanic circulation. His arguments will be found in detail in Vol. II. Part. 5 of these reports.

Dr. Böhnecke had mentioned to us before we started that the same trouble had been experienced on board Meteor and when ordering our instruments we asked Marx and Berndt to correct this error. Apparently they had not succeeded in doing so and we from our side have failed to test our instruments before we started our work.

Another experiment which we tried on one or two occasions is sketched in fig. 12. At the end of the sounding line SL a lever L is suspended with arms in the ratio 1 : 15. The short arm bears the sounding tube with hempen rope, bronze cable and reversing waterbottle, whereas the long arm is loaded with a weight W of about 1 KG. When the sounding tube reaches the bottom the lever is pulled over in the position indicated by dotted lines; thereby the rod R is pressed in tube T the hooks H catching the studs S. When the wire is next tautened again the lever swings back in its former position thereby releasing the messenger which operates the water bottle underneath. The idea was to trap the water sample at a distance from the bottom which is perfectly fixed and to be able to stop the sounding machine when paying out the wire without running the risk of the water bottle being closed at the wrong moment. As far as our experiments go the method seems practicable; when after a few trials, however, the sounding wire broke and the apparatus was lost no further attempts were made in this direction.

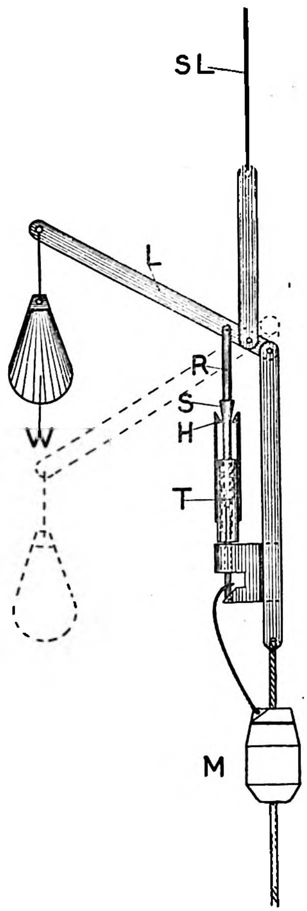

Fig. 12.

§ 4. SOME NOTES ON THE DISCUSSION OF ERRORS

Before entering on the discussion of the accuracy of our observations we will briefly explain some formulae which, though well known in the theory of statistics, are not as frequently applied

in error discussions of physical data as they merit. We will only deal with some fundamental principles; for a detailed treatment of the subject we refer to text books on the theory of statistics [1]).

In practically every physical observation the total error is the sum of a number of partial errors due to different sources of inaccuracy

$$E = e_1 + e_2 + e_3 + \ldots. + e_m \qquad 1)$$

In repeated experiments each of these partial errors will be distributed according to some frequency law

$$\text{Frequency of } e_k = f_k(e_k) \,.\, de_k$$

Whether the functions f_k are continuous or discontinuous is entirely immaterial for the following arguments though for the sake of simplicity we will allways consider them to be continuous.

We are still at liberty to fix the zero points for the various errors in a suitable way and in accordance with common practice these will be fixed so that the averages e_k are all zero

$$\overline{e_k} = \int_{-\infty}^{+\infty} e_k \,.\, f_k(e_k) \,.\, de_k = 0 \ldots. \qquad (2)$$

For error discussions a knowledge of the detailed shape of the frequency curves is unessential; only the magnitude of the errors is of interest and can adequately be represented by the standard error or standard deviation σ_k [2]) which is defined by

$$\sigma_k^2 = \int_{-\infty}^{+\infty} e_k^2 \,.\, f_k(e_k) \,.\, de_k \ldots. \qquad (3)$$

In various calculations it is often more convenient to work with σ^2 instead of with σ and for that reason σ^2 has been given a name of its own; it is called the „variance" a term that will be frequently used in the following.

Finally it should be noted that in the following discussions we are free to subdivide the total error in as many partial errors as we like; the sum of two errors $e_k + e_l$ can always be considered as a single error due the combined sources. It will be assumed, however, that the different partial errors are not correlated, that is, that the average products are all zero

$$\overline{e_k \,.\, e_l} = 0 \ldots. \qquad (4)$$

By a proper choice of the errors taken into consideration this can always be achieved.

Now by squaring equation (1) and taking the average we obtain making use of (4)

$$\overline{E^2} = \overline{e_1^2} + \overline{e_2^2} + \overline{e_3^2} + \ldots. + \overline{e_m^2}$$

or

$$\sigma^2 = \sigma_1^2 + \sigma_2^2 + \sigma_3^2 +; \ldots. + \sigma_m^2 \ldots. \qquad (5)$$

in words;

The total variance is equal to the sum of the partial variances or

The square of the total standard deviation equals the sum of the squares of the partial standard deviations.

This law is perfectly general; it is entirely independent of the special form of the frequency functions f_k which may be all different from one another, continuous or discontinuous or even skew.

In analysing the influence of different sources of error equation (5) is of very great utility and can be applied in a variety of ways as we will illustrate by a few concrete examples. Thereby it will for the present be supposed that the standard deviations σ figuring in our arguments are known with accuracy in which case conclusions can be drawn from (5) with certainty. In reality, however, this condition is never satisfied; the standard deviations can only be estimated from our observations, so that in using (5) we have to take into account the possible errors of these estimates. To the complicated problems which then arise we will briefly return on page 13.

Frequently observations are read off to a decimal point which greatly surpasses the inevitable errors and we are confronted with the question how far our readings may be rounded off without undue loss of accuracy. For instance if readings have been made to a second decimal 5.31, 6.76,

[1]) For instance G. U. Yule and M. G. Kendall. An introduction to the theory of statistics. Griffin and Co. London. 1937. R. A. Fisher. Statistical methods for research workers. Oliver and Boyd. London. 1934.

[2]) This quantity is also frequently called the mean square error but in accordance with statistical literature we will prefer the above terminology.

4.87 what will be the effect of rounding off to 0.05 that is replacing 5.31 by 5.30, 6.76 by 6.75 etc. In doing this we introduce an additional error e which takes the values —0.02, —0.01, 0.00, +0.01, and +0.02 with equal frequencies. The partial variance corresponding to these errors will be

$$\sigma_r^2 = \frac{1}{5} \Sigma e^2 = 2.0 \times 10^{-4}$$

Hence if the standard error of our observations was σ it will after rounding off be

$$\sigma' = \sqrt{\sigma^2 + 2.0 \times 10^{-4}}$$

by equation (5). By rounding off the error always increases but it will be clear that when the difference between σ and σ' is very small the advantage of retaining less decimals will outweigh the decrease of accuracy.

On board Meteor the temperature observations were made to 0,001 °C and from the data published in the Meteor Reports (Vol. IV. Part I) I calculated the standard error of a single observation (see page 18) to

$$\sigma = 7{,}2 \times 10^{-3}\,°\mathrm{C}$$

By rounding off to 0,005 °C this error would be increased to

$$\sigma' = \sqrt{(7{,}2^2 + 2{,}0)} \times 10^{-3} = 7{,}35 \times 10^{-3}\,°\mathrm{C}$$

and after rouding off twice to 0,005 °C, once in reading the thermometer and a second time in calculating the correction the error would increase to

$$\sigma'' = \sqrt{(7{,}2^2 + 4{,}0)} \times 10^{-3} = 7{,}45 \times 10^{-3}\,°\mathrm{C}$$

In both cases the increase in the error is insignificant.

In general rounding off to y (0,005 °C in the instances considered above) will introduce a partial error ranging from $-{}^1/_2 y$ to $+{}^1/_2 y$ with uniform frequency. Assuming a continuous distribution within this interval the corresponging variance is easily computed to be

$$\sigma^2 = \frac{1}{y} \int_{-\frac{1}{2}y}^{+\frac{1}{2}y} x^2 \,.\, dx = \frac{1}{12} y^2 \ldots. \qquad (6)$$

Taking $y = 0{,}05$ this would give $\sigma^2 = 2{,}1 \times 10^{-4}$ in stead of $2{,}0 \times 10^{-4}$ as derived above from a discontinuous frequency distribution. The difference is so small that it can be neglected.

Using equation (6) we find that rounding off the temperature observations to 0,01 °C would introduce an additional variance of ${}^1/_{12} \times 10^{-4}$ (°C)^2 so that the standard error increases to

$$\sigma^2 = \sqrt{(7{,}2^2 + 8{,}3)} \times 10^{-3} = 7{,}75 \times 10^{-3}\,°\mathrm{C}$$

Even in that case the accuracy is not seriously reduced so that it may be questioned whether it is not advisable to round off our temperature observations to 0.01 °C.

Another useful mode of applying equation (5) is the following. We have made obvervations at one depth but at various stations in a certain region. The differences in the temperatures observed will partly be due to real temperature variations but they are also caused by the variations due to internal waves. We may now calculate 1. the standard deviation from the observations at the different stations σ_1 and 2. the partial standard deviation due to internal waves from repeated observations at an anchor station σ_2; σ_2 represents a part of the variations comprised in σ_1 and it is at once evident that unless σ_1 is considerably greater than σ_2 the interpretation of a horizontal map of isotherms becomes doubtful owing to the uncertainties introduced by internal waves. The ratio $\sigma_1 : \sigma_2$ will provide an objective measure for the degree of confidence to be placed in such a horizontal section.

Again, suppose we have recognised two sources of error in some kind of experiment with partial standard errors $\sigma_1 = 1$ and $\sigma_2 = 2$ the total error being $\sqrt{1^2 + 2^2} = 2.25$; it is found at once that should we succeed by special precautions to reduce σ_1 from 1 to ${}^1/_2$ this would only slightly reduce the total error, but could we diminish σ_2 by 50% this would reduce the total error almost in the same degree. In general if one source of error predominates the accuracy is effectively increased when this error is reduced whereas it has very little effect if other sources of error are elminated. Though

this is perhaps an obvious conclusion with the aid of equation (5) it allows a precise formulation; once the errors have been properly analysed we can predict the gain to be expected from the different ways open for further refinement of our experiments.

We must now turn to the more important question how the standard errors σ must be estimated from our observation, what is the accuracy of this estimate and how it affects the applicability of equation (5). All these problems have been dealt with in extenso in the theory of statistics and we can here only restate the principal results.

Equation (5) as demonstrated above holds regardless of the special kind of frequency distribution followed by the different partial errors. In the present problem this point of view can not be maintained, since the accuracy of an estimated variance depends on the shape of the underlying frequency law. At the outset statistical theories have therefore started on the assumption that all errors considered should obey the normal law

$$f(x) \, . \, dx = \frac{1}{\sigma \sqrt{2\pi}} e^{-\frac{x^2}{2\sigma^2}} . \, dx \tag{7}$$

At a later stage it has been questioned how far the theoretical conclusions based on this assumption could also be applied to cases where the fundamental frequency distribution is not normal. Mainly by practical tests and experiments it has been ascertained that unless the deviations from the normal law are very extreme conclusions derived from this particular destribution can confidently be used in other cases as well. They will never lead to serious errors. Thus we may restrict ourselves to the normal frequency law and its consequences.

In that case given a set of n observations the best estimate for the variance σ^2 is

$$s^2 = \frac{\Sigma \, d^2}{(n-1)} \tag{8}$$

the d's being the deviations from the average in a series of n observations. The accuracy of this estimated variance is represented by the standard error

$$\sigma_{s^2} = \sigma^2 . \sqrt{\frac{2}{(n-1)}} \tag{9}$$

For the standard error we obtain similarly

$$s = \sqrt{\frac{\Sigma \, d^2}{(n-1)}} \text{ and } \sigma_s = \sigma . \sqrt{\frac{1}{2(n-1)}} \text{ [1]} \tag{10}$$

It will be noted from these formulae that even if we have a series of 10 or 20 observations the relative errors in the estimated variance or standard error are still of the order of 20 to 40%. Such inaccuracies render the direct application of equation (5) of doubtful value.

Fortunately, however, we are frequently in a position to calculate much more precise estimates of the variance; for if we do not possess a single series of observations sufficient in size we may have at our disposal a number of small series in all of which the same sources of error have been operative and which can therefore be combined. Suppose we have m series of $n_1, n_2, \ldots n_m$ observations respectively and from each set we have computed a variance s_k^2 according to formula (8); then since the error in s_k^2 is inversely proportional to $\sqrt{(n_k - 1)}$ the weight of s_k^2 will by the theory of least squares be proportional to $(n_k - 1)$ so that the separate estimates can be combined into the final value

$$s^2 = \frac{\Sigma(n_k - 1)s_k^2}{\Sigma(n_k - 1)} = \frac{\Sigma\Sigma \, d^2}{(N - m)} \tag{11}$$

where N is the total number of observations and m is the number of series in which they are subdivided; $\Sigma\Sigma d^2$ stands for the summation over the deviations from the averages in all the different series.

In the special case that we have only pairs of observations this equation simplifies to

$$s^2 = \frac{\Sigma \, D^2}{2n} \tag{12}$$

[1]) In these equations we have used the symbol σ to denote the theoretically correct value of the standard deviation, whereas the letter s indicates an estimate of σ calculated from a set of observations.

as is easily verified. In (12) n is the number of pairs and the D's are the differences between the pairs. This formula will for instance be used to compute the standard error of our temperature observations.

In analogy with equation (8) the standard error of the variance estimated by (10) will be

$$\sigma_{s^2} = \sigma^2 \cdot \sqrt{\frac{2}{(N - m)}} \tag{13}$$

which will need no further explication. The number (N — m) im formulae (10) and (12) is usually designated as the number of degrees of freedom from which s^2 has been computed; it is this number which determines the accuracy obtained.

If (N — m) is large σ_{s^2} will be small and s^2 will closely approach the true variance. Under such circumstances we can use equation (5) without serious restrictions inserting the estimated variances; thus for example in the discussion of rounding off errors on page 12 it will be quite immaterial whether the standard error of the temperature observation used is subject to some slight error or not.

This is no longer allowable, however, when the errors in the estimates s^2 become too large and for such cases special criteria have been developed. To illustrate this point let us again consider the case already dealt with on page 12.

Here we have

1. An estimate s_1^2 of the variance σ_1^2 of the temperature differences between different stations.
2. An estimate s_2^2 of the variance σ_2^2 correponding to variations caused by internal waves.

The variations σ_2^2 form a part of the variations σ_1^2 so that we may put

$$\sigma_1^2 = \sigma_2^2 + \sigma_3^2$$

where σ_3^2 represents the true temperature differences between the various stations. We see that σ_1^2 must be greater than σ_2^2 and we should consequently expect that s_1^2 will also be greater than s_2^2, but owing to the errors in these estimates this need not necessarily be the case. If s_1^2 should turn out the smaller of the two it is clear, however, that σ_3^2 cannot have been very large and it is impossible to draw any conclusions from our data concerning the existence of real temperature differences. Again if s_1^2 is very much larger than s_2^2 this may with confidence be attributed to a large value of σ_3^2 or to large variations in the real temperature. But if s_1^2 is only slightly larger than s_2^2 the case is a dubious one and requires a special treatment.

We now make the assumption that σ_3^2 is zero so that s_1^2 and s_2^2 are both estimates of the same variations. Moreover we suppose that the frequency law of these variations is the normal one

$$F(x) \cdot dx = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{x^2}{2\sigma^2}} \cdot dx$$

on this basis the probability P can be computed that the ratio $r = s_1^2/s_2^2$ will be as large as or greater than the value actually derived from our observations. This probability P depends on the number of degrees of freedom n_1 and n_2 from which the estimates s_1^2 and s_2^2 have been calculated but is independent of the value of the parameter σ in the above frequency law. Given n_1, n_2, and r, P can at once be found from a table computed for this purpose [1]).

Now if P is small — say 0.01 or less — we infer that our observations can hardly be reconciled with the hypotheses on which P was based. Besides it has been ascertained by numerous experiments that the value of P is insensitive against large variations in the shape of the frequency curve adopted, so that had we based our calculations on other frequency distributions we should have obtained very much the same value of P. Hence a small P indicates that the assumption that σ_3 is zero was presumably incorrect, so that our observations indicate the existence of true temperature differences between the different stations. The difference between s_1^2 and s_2^2 is said to be significant.

Similar criteria have been developed for a great variety of problems. They always consist in testing whether the data observed are likely to have occurred when a certain hypothesis is made. If the observations turn out to be a rather improbable result we are justified in rejecting the hypothesis;

[1]) In the actual test developed for this case $z = {}^1/_2 {}^e\log r = {}^e\log s_1/s_2$ is used instead of r, which introduces certain simplifications. Tables of P as a function of n_1, n_2 and z will be found in text books on the theory of statistics for instance those quoted on page. 11.

in the opposite case the hypothesis is an acceptable one though it may happen that other suppositions will fit the data equally well [1]).

One advantage of such methods is that they can be used however small the number of observations. In many of the applications made further on the number of observations used is so large, however, that it will not be necessary to have recourse to the the most critical methods, the accuracy of the standard deviations being sufficient to apply equation (5) directly. But it should be noted that in all critical tests the standard deviations and the number of degrees of freedom from which they were derived enter as fundamental quantities. Hence we will calculate these data whenever possible so that anyone who might desire to use a more precise method of reasoning will be able to do so.

§ 5. THE PROTECTED REVERSING THERMOMETERS AND THE TEMPERATURE DETERMINATIONS

A. Introduction and inventary

The principle of the protected reversing thermometer is illustrated in fig. 13. M is the main mercury reservoir from which the mercury rises through a piece of glass tube with a loop L in it and through a capillary C to a second small vessel V. With the reservoir M downwards the thermometer is lowered in the sea and kept at the desired level until temperature equilibrium has been established after which it is made to reverse. Thereby the thread of mercury breaks off in the constriction D a process which is made easier and more precise by the cul de sac branching off E.

The condition after reversal is sketched in fig. 13B. The volume of mercury cut off at point D has flowed down in the small vessel V from where it reaches some way up in the capillary C and indicates the temperature of the seawater on the scale S.

If the thermometer is now drawn up again its temperature rises as a rule. A quantity of mercury which may then by thermal expansion be pressed past the constriction D will be caught in the loop L and cannot spoil the observation. Moreover the reading on the scale S will slightly alter with the temperature of the entire instrument when the reading is carried out, and a corresponding correction must be applied. Hence a small ordinary thermometer T has been added from which the temperature of the instrument can be read.

To avoid the disturbing influence of the high pressures prevailing in the sea both thermometers have been mounted inside a closed glass cylinder. The space round M has been filled up with mercury to ensure a better heat conduction.

The reversing thermometer dates from the end of the 19th century but the first instruments made by Negretti and Zambra were imperfect so that an insulated water bottle with ordinary thermometers was often preferred. About 1900 Nansen suggested several improvements and new instruments manufactured by C. Richter in Berlin met with considerable succes. The process of improvement which has been going on since then was brought to its conclusion by the painstaking researches of the late Professor Merz when preparing the Meteor expedition. By him and

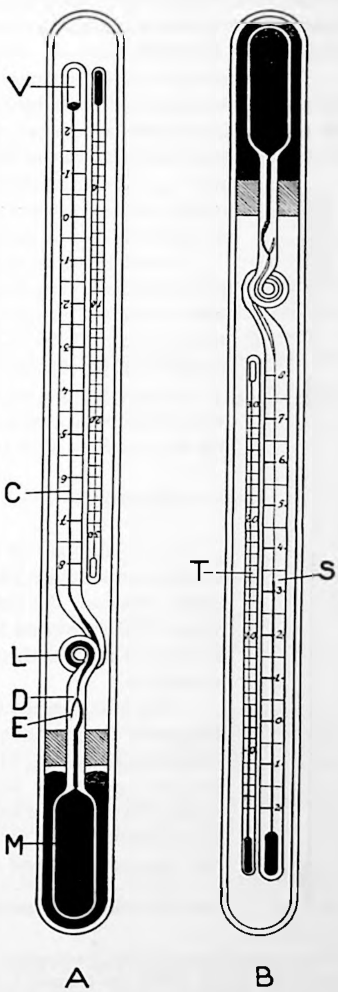

Fig. 13. The protected reversing thermometer.

[1]) To another instance of such statistical tests viz. that of comparing the averages from two different series of observations attention has been drawn by H. Müller. Ann. d. Hydrographie 1935, 224.

his collaborators the ways open for further refinement were carefully examined and several succesful improvements were introduced. On these Böhnecke [1]) has reported in detail.

We used the same instruments made by Richter and Wiese in Berlin. They are manufactured in two different types with scales divided in $^{1}/_{10}$ °C and $^{1}/_{20}$ °C respectively. In the following these two classes will be designated as the $^{1}/_{10}$ °C thermometers and the $^{1}/_{20}$ °C thermometers. The $^{1}/_{10}$ °C thermometer has a scale ranging from + 9 to + 30 °C and the $^{1}/_{20}$ °C goes either from + 3 to 13 °C or from — 2 to + 9 °C.

We were equipped with

23 $^{1}/_{20}$ °C thermometers reading from —2 to +9 °C
19 $^{1}/_{20}$ °C thermometers reading from +3 to +13 °C
and 30 $^{1}/_{10}$ °C thermometers.

Upon the whole they proved most excellent instruments and we fully agree with Böhnecke that it is difficult to imagine any further increase in the accuracy of the temperature determinations.

Our observations were carried out as follows:

At the desired depth the thermometers were kept for 10 to 20 minutes before they were made to reverse. After being hove on deck again they were placed in a special rack and left there for half an hour at least before the readings were made. They were read off only once the observations being rounded off to 0.005 °C.

The corrections were determined by the graphical method described by Sund [2]), using, however, the simpler formulae indicated by L. Möller [3]) in calculating the necessary data. This method includes a linear interpolation between the capillary corrections which were determined at the Physikalisch Technische Reichsanstalt in Berlin for every second and for every fourth degree for the $^{1}/_{20}$ °C and $^{1}/_{10}$ °C thermometers respectively. The zero points were checked three times in the course of the expedition and the corresponding corrections were applied until a new determination was made.

It will be noted that we did not pay such elaborate attention to the accuracy of our observations as was done on board Meteor where the thermometers were placed in a water bath to ensure a uniform temperature and where the readings and corrections were made to 0.001 °C. In what measure this may have influenced the accuracy of our results will be discusses further on.

Altogether we have carried out about 6800 temperature observations; of these 2740 were made with two instruments and in the remaining 4060 cases only one thermometer was used, so that in total the thermometers were used 9540 times.

B. Defects

In a number of cases the reversing thermometers failed to register at all. This defect occurred in 190 out of the 9540 times the instruments were used; only in 56 cases, however, the defective instrument was used singly so that the observation was spoiled. Moreover on 8 occasions the observation could be repeated with a second series so that the net loss through defects of the thermometers amounts to 48 out of 6800 observations.

The instruments failed in different ways but one special defect was by far the most frequent; the mercury in the main reservoir came off from the glass wall the result being as illustrated in fig. 14. About 35 thermometers have shown this defect though mostly only on one or two occasions; some however were very persistent and had to be put out of use. Having been left to themselves for several months they often proved trustworthy instruments again for a short while; but sooner or later the old failure returned and the thermometer had to be set aside again.

Fig. 14. The most frequent defect of the reversing thermometers.

[1]) Meteor Reports. Vol. IV. Part. I. p. 208 ff.
[2]) O. Sund. Journ. de Conseil 1. 1926 p. 242.
[3]) L. Möller. Ann. der Hydrographie 61. 1922 p. 58.

In the capillary directly above the large mercury reservoir (point B in fig. 14) a constriction has been made probably in order to prevent defects of the kind just described. If, however, this constriction is made too narrow there will be some danger of the mercury breaking off at this point instead of at point C. This we have observed to happen though not very frequently. In the new instruments developed by the Meteor expedition the distance from B to C was enlarged to make the breaking off point C directly visible. Perhaps both defects are to some degree a consequence of this alteration.

C. Abnormal errors

The reversing thermometers are very accurate, the errors being of the order of 0.01 °C. If therefore the indications of two instruments used together should differ by more than 0,05 °C one of the readings must be seriously wrong. If the discrepancy is large it will be easy to decide which instrument was in error by comparing with the other observations at the same station but when the difference is small this will be of little help.

Errors of this type sometimes occurred but very rarely. In 21 out of 2740 cases the discrepancy between a pair of thermometers was between 0.06 and 3.00 °C; only in 8 of these cases it was impossible to decide which instrument had given an erroneous temperature and in these 8 instances the difference was always less than 0.4 °C.

The same kind of error will be less easy to detect when only one thermometer is employed, but they are too infrequent seriously to reduce the value of our observations. On the other hand we will be justified in rejecting a few observations based on a single thermometer, if they do not fit the depth-temperature curve at all.

D. Normal errors

We now proceed to a discussion of the normal errors which are inevitable in all observations. If we have n pairs of observations the standard error of a single measurement with one thermometer is estimated by $s = \sqrt{\frac{\Sigma D^2}{2n}}$, where D denotes the difference between the indications of the two instruments (see page 13). From our own data and from the error frequencies published in the Meteor Reports [1]) the following values have been computed in this way.

TABLE 4. Standard errors of a single temperature observation.

	Snellius		Meteor	
	s in °C	n	s in °C	n
$^1/_{20}$ °C Thermometers. . . .	8.9×10^{-3}	852	8.3×10^{-3}	1890
$^1/_{10}$ °C Thermometers. . . .	10.7×10^{-3}	561	12.5×10^{-3}	854

n gives the number of pairs of observations used.

In calculating the Snellius values we have not used all our data. In the case of the 1/10 °C instruments we took into account only about one half of our observations as we did not consider the problem sufficiently important to aim to the highest precision. In connection with investigations of a different kind we have for the 1/20 °C thermometers only considered those cases where the same pair of instruments was employed at least four times.

The $^1/_{20}$ °C thermometers were slightly more accurate on board Meteor than on board Snellius, whereas the $^1/_{10}$ °C thermometers seem to have been slightly more accurate in our case but the differences are not of great importance.

A more detailed analysis can be carried out by plotting error frequency curves and the data at hand are sufficiently numerous for this purpose. Below this has been done for the $^1/_{20}$ °C thermometers only.

If we use the frequencies of the differences between the readings of two thermometers used

[1]) Meteor Reports Vol. IV. Part. I. p. 240.

at the same depth it must be remembered that from a theoretical point of view one half of these differences must be considered to be negative the other half being positive; the difference 0.01 °C having for instance occurred n times the frequencies will be $^1/_2$n for — 0.01 °C and $^1/_2$n for + 0.01 °C. If we omit this reduction the frequency for zero difference will be a factor 2 too small in comparison with the others. We are led to the same result when we consider the deviation from the average temperature; for a difference of 0.01 °C is equivalent to deviations of — 0.005 and + 0.005 °C, while a difference zero between two instruments contributes twice to the frequency for zero deviation.

Since in the Meteor Reports the frequencies of the deviations from the average temperature have been given we will do the same, so that our data are at once comparable. Our readings were rounded off to 5×10^{-3} °C and the deviations are consequently subdivided in intervals of 2.5×10^{-3} °C. The frequencies are given in table 5.

TABLE 5. Frequencies of deviations from the average for two $^1/_{20}$ °C thermometers used together.

Deviation in 10^{-3} °C	Frequency	Frequency in %	Deviation in 10^{-3} °C	Frequency	Frequency in %
0.0	276	16.2	12.5	36	2.1
2.5	237	13.9	15.0	13	0.75
5.0	195	11.4	17.5	4	0.2
7.5	140	8.2	20.0	2	0.1
10.0	87	5.1			

The frequencies of negative deviations are equal to those of positive deviations of the same absolute value. In computing the percentage frequencies the negative deviations have also been taken into account.

In figure 15B these frequencies have been compared with the normal frequency curve

$$\frac{1}{s\sqrt{\pi}} e^{-\frac{x^2}{s^2}} . dx \text{ [1])}$$

using for s the value of table 4. The agreement between theory and observation is quite satisfactory.

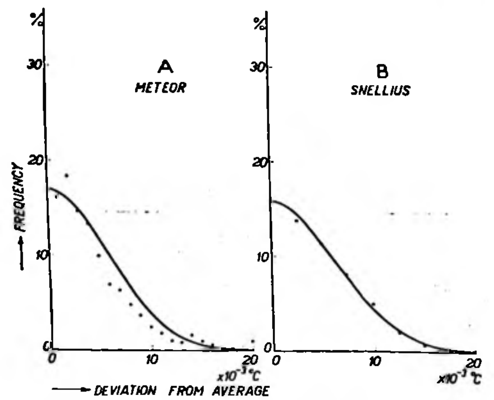

Fig. 15. Frequencies of deviations from the average temperature for Meteor and Snellius compared with the corresponding normal error curve.

In fig. 15A the Meteor data have been treated in a similar way but in this case the theoretical curve does not fit the observations at all well. To judge from this figure the Meteor observations up to 12×10^{-3} °C will fit an error curve with a smaller standard error than that given in table 4. To settle this point the natural logarithm of the frequency has been plotted against the square of the deviation in fig. 16. Up to 12×10^{-3} °C the points can reasonably be represented by a straight line as we should expect when the error curve holds. The standard error derived from the slope of this line is

$$7{,}2 \times 10^{-3} \text{ °C}$$

against $8{,}3 \times 10^{-3}$ °C computed in table 4. As it is clearly seen from fig. 16 the difference is due to the abnormally high frequencies of deviations greater than 13×10^{-3} °C.

In Vol. IV. Part II of the Meteor Reports which contains the complete tables of the oceano-

[1]) If the error of a single observation is described by the frequency formula

$$f(x) . dx = \frac{1}{s\sqrt{2\pi}} e^{-\frac{x^2}{2s^2}} . dx$$

the deviations from the average in pairs of observations are given by

$$\frac{1}{s\sqrt{\pi}} e^{-\frac{x^2}{2s^2}} . dx$$

Hence this last formula has been used in computing the curves in fig. 15.

graphic observations the deviations from the average temperature have been separately entered. Selecting from these tables the cases in which the deviation was 15 × 10^{-3} °C or greater it is found that these large deviations occurred chiefly with a few special thermometers, so that the high frequencies of large deviations in the Meteor data are due to three or four bad instruments. Apparently we had on board Snellius a set of more homogeneous quality. If so it will be better in comparing Snellius and Meteor to disregard the large deviations in the latter and represent

the Meteor by a standard error of
7.2 × 10^{-3} °C
and the Snellius by a standard error of
8.9 × 10^{-3} °C

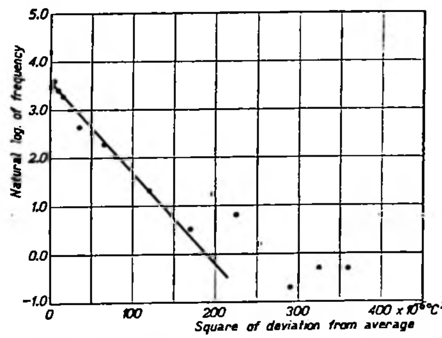

Fig. 16. Natural logarithm of the Meteor frequencies plotted against the square of the deviations from the average.

As will be demonstrated below this difference in accuracy can satisfactorily be accounted for by the different methods of observation adopted in both cases.

In fig. 15A and 16 the Meteor data show a high peak at zero. This peak is not apparent in the frequencies as given by Böhnecke (Vol. IV Part I. p. 242); but as explained above these frequencies, referring to deviations regardless of sign, must be halved except that at zero and thereby the peak comes into existence [1]). Probably, however, this peak is not real. From Vol. IV Part II of the Meteor Reports the frequencies of the various deviations can be separately computed and in doing this I obtained results which markedly deviate from the data given by Böhnecke in Vol. IV Part I as is illustrated by the following table.

TABLE 6. Frequencies of deviations from the average temperature as given in Vol. IV Part I and as computed from Vol. IV Part II of the Meteor Reports.

Deviation zero

Profile	1	2	3	4	5
Frequency Vol. IV Part I . . .	22	35	49	22	58
Frequency Vol. IV Part II . . .	8	27	19	12	27

Deviation 1 × 10^{-3} °C

Profile	1	2	3	4	5
Frequency Vol. IV Part I . . .	19	40	30	32	56
Frequency Vol. IV Part II . . .	19	51	57	41	69

The data in this table refer to the 1/10° C and the 1/20° C thermometers together.

We see from this table that the frequencies for zero deviation computed from Vol. IV Part II are approximately half as large as those given in Vol. IV Part I, whereas for 1.0 × 10^{-3} °C the former are considerably greater than the latter. The temperatures were determined on board Meteor to 1.0 × 10^{-3} °C so that the deviations from the average must originally have been grouped in intervals of 0.5 × 10^{-3} °C. The above discrepancies might therefore be explained by assuming that a deviation of 0.5 × 10^{-3} °C has been rounded off by Böhnecke (Vol. IV Part I) to 0.0 × 10^{-3} °C and by Wüst (Vol. IV Part II) to 1.0 × 10^{-3} °C, or some similar difference in the method of treating the observations. If the data are published in such detail as done by the Meteor greater attention should

[1]) It should also be noted that the Meteor data were divided in 0,001° C intervals so that all frequencies were multiplied by 2,5 in order to render them comparable with our own data which were grouped in 0,0025° C intervals.

be paid to this point. It will be understood that with the frequencies computed from Vol. IV Part II the peak at zero in fig. 14A would dissappear.

Let us now investigate in what measure the different methods used on board Snellius and Meteor can account for the differences in the standard errors derived from the observations.

Comparing our methods we have.

1. The readings, the calculation of the corrections and the determination of the zero point corrections were carried out to 0.001 °C on board Meteor whereas we rounded them off to 0.005 °C. As explained on page 12 the corresponding partial variance will be given by

$$\sigma_1^2 = 3 \times \frac{5^2}{12} \times 10^{-6} = 6.3 \times 10^{-6}\ (°C)^2$$

2. The scale corrections determined at the P.T.R. were rounded off to 0.01 °C for our instruments against 0.005 °C for those of the Meteor. This will again by the methods explained in § 4 introduce an extra variance in our case

$$\sigma_2^2 = \left(\frac{10^2}{12} - \frac{5^2}{12}\right) \times 10^{-6} = 6.3 \times 10^{-6}\ (°C)^2$$

3. Finally the scale corrections were determined at every degree for the Meteor and at every second degree for our instruments. From data kindly put at my disposal by Dr. Böhnecke I have estimated the error introduced thereby (see page 22) to be

$$\sigma_3^2 = 13.6 \times 10^{-6}\ (°C)^2$$

Taken together these sources will contribute to the error by

$$\sigma^2 = \sigma_1^2 + \sigma_2^2 + \sigma_3^2 = 26 \times 10^{-6}\ (°C)^2$$

so that by the extra precautions of the Meteor expedition we might have reduced the mean square error of our observations from

$$8,9 \times 10^{-3}\ °C \text{ to } \sqrt{\{(8,9)^2 - 26\}} \times 10^{-3} = 7,3 \times 10^{-3}\ °C$$

a result which closely approaches the value derived from the Meteor observations (see page 19).

It will be noticed that the main part of the difference is due to the fact that our scale corrections were given for intervals of two degrees and were rounded of to 0.01 °C. That we made our readings and corrections only to the nearest 0.005 °C is comparatively of small consequence. Before reading the instruments on the Meteor they were placed in a waterbath while we left them standing in air. Our analysis seems to indicate that this measure has not materially contributed to the greater accuracy of the Meteor temperatures.

Some of the measures adopted by the Meteor involve a considerable amount of extra work and we have insisted on the above investigation in order to get a proper idea of what the gain in accuracy may be. Whether the increase in accuracy is actually worth the time spent in reaching it is of course a matter of personal taste. I think, however, that in the open ocean where the temperature differences between different stations are as a rule of the order of 0.1 °C or more it will be of no consequence whatever whether the errors are 7 or $9 \cdot 10^{-3}$ °C. Perhaps such a difference may be of significance in regions where the temperature is practically constant over a large area as for instance in the deep sea basins visited by the Snellius. Under such circumstances it is possible, however, to attain a still higher accuracy by purely experimental methods. For the errors in observations made at approximately the same temperature and with the same instrument will for a large part be of a systematic nature, so that they can be eliminated by carefully comparing our instruments with each other. And a deep sea basin of almost constant temperature provides an ideal thermostate for this purpose; from observations made at the same depth with a number of different thermometers we may derive corrections to be applied to the readings of the individual instruments by which the systematic errors are compensated. Let us investigate how much the accuracy could possibly be increased by this procedure.

In table 7 two sets of thermometers have been compared at a number of subsequent stations. We see that 1858 always gives a higher reading than 1905, and that 1916 registers a lower temperature than 1855, the average differences being + 0.021 °C and — 0.028 °C respectively. In the same way the systematic differences were calculated for all cases where two thermometers were used at least

TABLE 7. Systematic differences observed between pairs of thermometers.

Instruments No. 1858—1905			Instruments No. 1916—1855		
Station	Temp. °C	Diff. °C	Station	Temp. °C	Diff. °C
297	3.7	+ 0.02	337	3.7	— 0.03
301	3.7	+ 0.02	338	3.8	— 0.03
302	3.8	+ 0.025	340	3.9	— 0.03
303	3.7	+ 0.02	341	4.5	— 0.02
310	3.7	+ 0.02	342	3.8	— 0.025
311	3.7	+ 0.02	343	4.4	— 0.025
312	3.7	+ 0.02	344	3.8	— 0.035
Average diff.		+ 0.021			— 0.028

four times together. As a rule these differences were not so large as in the instances given in table 7 as will be seen from the frequencies produced in table 8. These systematic errors form a part of the

TABLE 8. Frequency of systematic differences between two thermometers used together at least four times.

Diff.	Freq.	Diff.	Freq.
0.00 °C	23	0.020 °C	5
0.005	28	0.025	0
0.010	24	0.030	1
0.015	22		

total errors in our observations and by means of equation (12) on page 13 we find that this part is represented by a partial standard error $s = 7.3 \times 10^{-3}$ °C. Hence if the systematic errors could be completely eliminated the accuracy of our temperature determinations would increase

$$\text{from } 8.9 \times 10^{-3}\,°\text{C. to}$$
$$\sqrt{8.9^2 - 7.3^2} \times 10^{-3} = 5.1 \times 10^{-3}\,°\text{C}.$$

indeed a considerable improvement.

On board Snellius the method described has not been used to its full advantage though some attempts were made. Especially from station 170 to 312 the thermometers employed for deep sea observations were frequently interchanged so that each instruments was compared with several others. On the basis of these data extra corrections given in table 9 were applied to the readings of

TABLE 9. Corrections based on the mutual comparison of our thermometers on stations 172 to 312 for temperatures between 3 and 4 °C.

Therm. No.	Corr.	Therm. No.	Corr.	Therm. No.	Corr
1855	0,00	1880	+ 0,005	1915	+ 0,005
1857	+ 0,01	1881	0,00	1916	+ 0,005
1858	— 0,005	1905	+ 0,005	1920	+ 0,01
1859	+ 0,005	1906	— 0,02	1922	0,00
1861	— 0,01	1907	— 0,015	1924	+ 0,005
1862	— 0,005	1908	+ 0,005	1927	+ 0,005
1874	— 0,005	1909	— 0,005	1961	— 0,005
1875	0,00	1910	0,00	1962	+ 0,01
1878	+ 0,005	1911	+ 0,005		

the separate thermometers. For the stations mentioned these corrections reduced the standard error

of a single observation from 9.2 to 7.1 $\times$ 10^{-3} °C. As indicated, more systematic observations would probably lead to better results though it is doubtful whether the theoretical limit will ever be reached in practical cases.

It should be remarked that the systematic errors will for a large part be due to errors in the scale corrections; since these will be different for different parts of the temperature scales the method can effectively be used only over a small range of temperatures.

We now proceed to a discussion of some details concerning the use of the protected thermometers on board Snellius.

a. Accuracy of the corrections

As mentioned on page 16 the corrections were determined by Sund's graphical method. To find the accuracy of this procedure 10 corrections read off from the graphs were compared with the values resulting from a precise calculation. The root mean square difference amounted to 3×10^{-3} °C.

b. The accuracy of the scale corrections

As mentioned earlier the scale corrections for the $^1/_{20}$ °C thermometers were determined at every second degree, while on board Meteor they were known for every single degree. Dr. Böhnecke kindly put at our disposal [1]) the original data for the Meteor instruments and from these we may estimate the magnitude of the errors introduced by calibrating the thermometers at greater intervals.

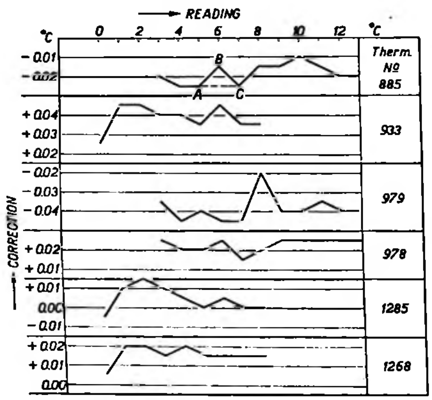

Fig. 17. Capillary corrections for some of the Meteor thermometers.

The scale corrections for some of the Meteor instruments have been plotted in fig. 17. Let us for the moment assume that the straight lines connecting the different points represent the exact corrections. Then if the corrections were known for 2° intervals only we should for instance for instrument No 885 from 5 to 7 °C apply a correction according to the straight line AC in stead of the broken line ABC. The difference reaches a maximum of 0.01 °C at 6 °C. In a large material there will on the average be an equal chance for an observation to fall anywhere in the interval from 5—7 °C so that errors from 0.00 to 0.01 °C will occur with equal frequency. The corresponding contribution to the variance of the temperature observations will be

$$\sigma^2 = \int_0^{0.01} \frac{x^2 \, . \, dx}{0.01} = \frac{(0.01)^2}{3} = 33 \times 10^{-6} \, (°C)^2$$

We have of course to take into account all the 2° intervals for all the thermometers and not this one particular interval only. From the data of the Meteor I read the difference between the linearly interpolated and the true correction in the middle of 113 intervals of 2 °C. The resulting frequencies have been entered in table 10 (p. 23).

The mean square amounts to 41×10^{-6} (°C)² and on the basis of the above equation the corresponding contribution to the variance of the temperature observations will be

$$\sigma^2 = \frac{41 \, . \, 10^{-6}}{3} = 1{,}36 \times 10^{-6} \, (°C)^2$$

This estimate is based on the assumption that the broken tract (ABC in fig. 17) represents the true correction. Drawing a smooth curve through the different points in stead would increase the esti-

[1]) For which we should like to express our gratitude here.

TABLE 10. Frequency of difference between interpolated correction and actual correction in the centre of 2 °C intervals derived from the Meteor data.

Difference 10^{-3} °C	Frequency	Difference 10^{-3} °C	Frequency
0.0	19	12.5	3
2.5	36	15.0	0
5.0	30	17.5	3
7.5	15	20.0	1
10.0	5	22.5	1

Mean square = $41{,}0 \times 10^{-6}$ (°C)^2
Root mean square 6.4×10^{-3} °C.

mated σ^2, so that the value obtained will be on the low side. On page 20 it has already been shown that the errors in the corrections here considered were for a large part responsible for the difference in accuracy between our observations and those of the Meteor expedition.

E. The determination of the volume V and its accuracy

With the customary notations

T_w = true temperature
T = temperature read off from the main thermometer
t = temperature at which the reading is made
V = zero point volume in °C
$1/a$ = linear expansion coefficient of mercury relative to that of glass
c = scale correction

we have the relation

$$T - T_w = \frac{(V + T_w)\ (t - T_w)}{a} - c \qquad (1)$$

where c will be the capillary correction at the reading T. When we have made two readings T_1 and T_2 at temperatures t_1 and t_2 we obtain by subtracting the corresponding equations

$$T_1 - T_2 = \frac{(V + T_w)\ (t_1 - t_2)}{a} - (c_1 - c_2) \qquad (2)$$

or rearranging

$$V = a \times \frac{(T_1 - T_2) + (c_1 - c_2)}{t_1 - t_2} - T_w \qquad (3)$$

and from this formula V may be computed.

T_w can be approximated with sufficient accuracy by linear inter or extrapolation between T_1, t_1 and T_2, t_2. The difference $c_1 - c_2$ of the scale corrections at T_1 and T_2 has to be determined from the corrections known for each instrument. In the calculations reported below this has always been done by linear interpolation. The values thus obtained will be subject to errors which are as a rule perfectly negligible. In one case, however, our observations indicated that this was not allowable (see page 25).

The accuracy of V calculated from equation (3) will mainly depend on the reading errors in T_1, T_2, t_1 and t_2 and the influence of such errors will be the smaller the larger the difference between t_1 and t_2. To be more precise the errors in V will be proportional to $1/(t_1 - t_2)$ so that by the theory of least squares the weight of V will be proportional to $(t_1 - t_2)^2$. Thus if we have computed n independent values V_k with weights P_k they will combine to the final result

$$V = \frac{\Sigma P_k \cdot V_k}{\Sigma P_k} \qquad (4)$$

Denoting the difference $V_k - V$ by d_k we have in addition

$$s_1 = \sqrt{\frac{\Sigma P_k \cdot d_k^2}{(n-1)}} = \text{standard error of a V with weight 1} \tag{5}$$

$$s_V = \sqrt{\frac{\Sigma P_k \cdot d_k^2}{(n-1) \cdot \Sigma P_k}} = \text{standard error of the final V given by (4)} \tag{6}$$

The derivation of these formulae may be found in any text book on the theory of least squares.

In point of principle a more accurate way to compute V would be to treat T as a linear function of t (equation (1)) $T = At + B$ and calculate the constant A (and from it V) by the least square formulae appropiate to this case. This method, however, involves much more elaborate calculations; moreover we made all our readings either at a tropical temperature of 25—30 °C or at a temperature of about 0 °C, always combining a high and a low reading for computing V. Under these conditions the formulae given above yield practically the same result as the linear function method as was ascertained by treating some cases in both ways.

At the Experimental Station of the Java Sugar Industry at Pasoeroean [1]) where we made our zero point determinations we also had an excellent opportunity to check the V's of our thermometers. The readings, 8 to 14 for each instrument, were made partly at the normal tropical temperature of 25—30 °C and partly in the spacious cold chambers of the institute at a temperature of about 0 °C. From these readings 4 to 7 independent V's were computed and finally combined according to equation (4). The weight assigned to each V was put equal to $\frac{(t_1 - t_2)^2}{100}$ which means that a determination with $t_1 - t_2 = 10$ °C has a weight unity.

TABLE 11. Original readings and calculation of the volume V for thermometer 1924.

Original readings

No.	T °C	t °C	T_w °C	No.	T °C	t °C	T_w °C
1	8.925	— 0.15		9	5.225	— 0.4	
2	8.947	0.85		10	5.23	0.45	
3	8.95	0.9		11	5.348	6.0	
4	9.09	8.0		12	5.575	18.1	5.3
5	9.415	24.65	9.1	13	5.71	25.1	
6	9.465	26.9		14	5.775	28.6	
7	9.495	28.4					
8	9.505	29.2					

Calculations

Read. comb.	$T_2 - T_1$	$t_2 - t_1$	$C_2 - C_1$	T_w	V_k	P_k	V	d_k
8—1	0.58	29.35	0.00	9.1	111.2	8.5		— 0.2
7—2	0.548	27.55	0.00	9.1	112.1	7.5		0.7
6—3	0.516	26.0	0.00	9.1	111.9	6.5		0.5
5—4	0.325	16.65	0.00	9.1	109.9	3.0		— 1.5
							111.4	
14—9	0.54	29.0	0.003	5.3	110.3	8.5		— 1.1
13—10	0.48	24.65	0.002	5.3	113.3	6.0		1.9
12—11	0.227	12.0	0.001	5.3	109.9	1.5		— 1.5

A set of readings with the calculations made from them have been entered in table 11 while the final results for all instruments have been compiled in table 14 on page 26 ff. It will be

[1]) We should like to express our sincerest thanks to the managing board of the Experimental Station for t way in which they facilitated and promoted our work.

noted that in a few cases which are separately given in table 12 the differences between our own values and those originally given by Richter and Wiese largely exceed the possible errors. After our return some of these instruments were at our request checked again by Richter and Wiese and they then confirmed our observations. In the original calibrations some serious errors must therefore have been made.

TABLE 12. Large discrepancies between the volumes V as determined by us (V_c) and as given by Richter and Wiese (V_r).

Therm. No.	V_c °C	V_r °C	$V_c - V_r$ °C	Therm. No.	V_c °C	V_r °C	$V_c - V_r$ °C
1856	82.7	106	— 23.3	1885	205.4	217	— 11.6
1882	99.9	109	— 9.1	1889	200.2	218	— 17.8
1947	124.0	131	— 7.0	1890	213.2	181	— 32.2

Omitting these exceptional cases we have

	$^1/_{20}$ °C Thermometers	$^1/_{10}$ °C Thermometers
Standard difference between V_c and V_r $= D = \sqrt{\frac{\Sigma(V_c - V_r)^2}{n}} =$	0,9 °C	1,8 °C
Standard error in $V_c = s = \sqrt{\frac{\Sigma s_v^2}{n}} =$	0,45 ,,	0,8 ,,
Standard error in $V_r = \sqrt{(D^2 - s^2)} =$	0,8 ,,	1,6 ,,

Except for the instruments in table 12 we have computed the temperature corrections with the volumes V_r given by Richter and Wiese. For the $^1/_{20}$ °C thermometers the average volume was about 110 °C so that a standard error in V of 0.8 °C corresponds to an error of 0.75% in the correction, which produced in its turn an error of 0.003 °C in the temperature observations, the correction being, for the deep sea observations at least, always about 0.40 °C. For the $^1/_{10}$ °C thermometers the same error will be 1.5% of the correction; as the corrections, however, with these instruments varied from 0.0 to 0.30 °C the errors in the temperature observations will have varied between the corresponding limits.

It will be understood that for the expansion constant a in formula (3) the same value must be used as is taken in calculating the corrections. The exact value of a is then of little consequence; for if we take a slightly erroneous value the error made in computing the corrections will automatically be compensated by a corresponding error in V. For instance if $a = 6100$ and $V = 110$ °C were the correct data, we should with $a = 6350$ have obtained $V = 114.5$ °C and it is easily ascertained that the corrections calculated with either set of values will even under the most unfavourable circumstances differ by not more than 0.002 °C. On board Snellius we took $a = 6100$.

It has been mentioned above that a systematic error in V may arise from the fact that the difference $c_1 - c_2$ is not exactly known. An error of this kind is indicated by our observations with the unprotected thermometer No 1897. Two series of 8 readings made respectively with $T_w = 0.0$ °C and $T_w = 28.7$ °C gave the following results

$$\text{at } T_w = 0.0\text{ °C} \qquad V = 238.9 \pm 0.9\text{ °C}$$
$$\text{at } T_w = 28.7\text{ °C} \qquad V = 231.9 \pm 0.8\text{ °C}$$

The difference is too large to be merely accidental; if we attribute the discrepancy entirely to an error in the corrections $c_1 - c_2$ this error must have amounted to 0.03 °C. In this instance it would follow that the scale correction had altered by 0.03 °C over an interval of 2 °C which is not impossible. The corrections for the unprotected thermometer 1897 were known only for every tenth degree so that no further information is to be had from them. To avoid errors of this nature it seems advisable, however, always to determine the volume V at least at two different values of the true temperature T_w.

Volumes V calculated from different readings at the same value of T_w will vary amongst them-

selves only through the reading errors made in the readings of T and t so that inversely the magnitude of these errors can be derived from the errors in V. It is impossible to separate the errors in T from those in t but assuming the readings of the auxiliary thermometer t to be correct we may investigate what errors in T would be required to cause the observed variations in V. In reality these errors represent the combined influence of the reading errors for both the main and the auxiliary thermometer.

From the standard error s_1 as given by equation (5) of a volume V with weight 1 (that is with $t_1 - t_2 = 10$ °C) we may calculate the corresponding error in the difference $T_1 - T_2$ by

$$s = \frac{10 \cdot s_1}{a}$$

and this in its turn corresponds to a standard error in a single reading

$$s_T = \frac{s}{\sqrt{2}} = \frac{10 \cdot s_1}{a\sqrt{2}} \tag{7}$$

The errors computed by equation (7) have been entered in the last colum of table 14. To calculate a final value we will take the root mean square of these errors, which by the theory of statistics is a better estimate than the average.

We thereby obtain

TABLE 13. Standard reading errors for various types of instruments.

$^1/_{20}$ °C thermometer	0.003 °C
$^1/_{10}$ °C thermometer	0.0045 °C
Unprotected thermometers divided in $^1/_{10}$ °C	0.005 °C
Unprotected thermometers divided in $^1/_5$ °C	0.007 °C

As we should expect the errors increase with the intervals in which the scale is subdivided but for the instruments graded in $^1/_5$ °C they are only twice as large as for those with $^1/_{20}$ °C intervals.

TABLE 14. Zero point volumes V.

N = Number of the thermometer.
n = Number of observations from which V was computed.
V_c = value of V calculated from our own observations.
s_V = mean square error of V according to equation (6).
V_R = value of V as given by Richter and Wiese.
d = the difference $V_c - V_R$.
s_T = mean square reading error calculated by equation (7).

A. $^1/_{20}$ °C thermometers.

N	n	V_c °C	s_V °C	V_R °C	d °C	s_T in 10^{-3} °C
1872	10	92.7	0.25	94	— 1.3	1.7
1905	14	119.3	0.25	121	— 1.7	2.1
1906	14	107.9	0.5	108	— 0.1	3.5
1907	14	110.8	0.25	110	+ 0.8	1.8
1908	14	116.3	0.45	116	+ 0.3	3.0
1909	14	106.7	0.35	107	— 0.3	2.6
1910	14	118.0	0.45	118	0.0	3.3
1911	14	100.2	0.45	101	— 0.8	3.0
1914	6	96.5	0.25	96	+ 0.5	1.1
1915	12	100.2	0.4	100	+ 0.2	2.9
1916	8	103.8	1.2	105	— 1.2	8.0
1917	14	101.3	0.45	101	+ 0.3	3.5

N	n	V_c °C	s_V °C	V_R °C	d °C	s_T in 10^{-3} °C
1961	10	109.3	0.3	109	+ 0.3	2.1
1962	8	79.8	0.3	81	— 1.2	2.2
1854	14	99.4	0.5	99	+ 0.4	3.6
1855	14	103.5	0.15	103	+ 0.5	1.1
1856	16	82.7	0.4	106	—23.3	3.3
1857	14	102.0	0.35	103	— 1.0	2.9
1858	14	105.8	0.25	106	— 0.2	1.9
1859	14	104.4	0.45	104	+ 0.4	3.3
1861	14	106.4	0.35	108	— 1.6	2.7
1862	12	96.9	0.55	98	— 1.1	4.0
1656	14	102.2	0.4	102	+ 0.2	2.9
1651	10	102.9	0.25	102	+ 0.9	1.6
1874	8	104.0	0.3	105	— 1.0	1.8
1875	8	106.4	0.25	107	— 0.6	1.5
1876	8	99.9	0.2	101	— 1.1	1.3
1877	6	110.2	0.9	110	+ 0.2	4.6
1878	8	97.1	0.6	96	+ 1.1	3.5
1880	10	105.0	0.35	106	— 1.0	2.3
1881	8	112.4	0.4	112	+ 0.4	2.7
1882	12	99.9	0.4	109	— 9.1	3.0
1920	14	103.8	0.35	104	— 0.2	2.8
1921	14	118.1	0.3	117	+ 1.1	2.2
1922	14	103.7	0.3	104	— 0.3	2.5
1923	14	106.5	0.55	107	— 0.5	3.6
1924	14	111.4	0.35	111	+ 0.4	2.4
1925	14	118.4	0.2	119	— 0.6	1.8
1926	14	115.3	0.35	116	— 0.7	2.3
1927	14	105.1	0.4	105	+ 0.1	2.8
1928	14	114.3	0.3	115	— 0.7	2.0
1929	—	—	—	—	—	—

B. The $^1/_{10}$ °C thermometers.

1636	8	114.3	0.4	113	+ 1.3	2.5
1637	8	102.5	0.9	103	— 0.5	6.0
1943	8	146.4	0.45	148	— 1.6	2.9
1944	8	119.2	0.8	118	+ 1.2	5.2
1947	8	124.0	0.5	131	— 7.0	3.0
1950	8	133.7	0.9	136	— 2.3	5.0
1951	8	134.1	0.9	135	— 0.9	4.8
1952	8	119.2	0.5	120	— 0.8	2.6
1954	8	121.8	0.95	123	— 1.2	5.2
1955	8	125.7	1.2	123	+ 2.7	6.3
1956	8	127.3	0.35	131	— 3.7	3.1
1957	8	120.6	0.35	123	— 2.4	2.0
1958	8	126.4	0.4	124	+ 2.4	2.6
1959	8	120.0	1.1	121	— 1.0	6.3
1960	8	132.5	0.2	133	— 0.5	6.7
1974	8	112.0	1.6	111	+ 1.0	11.0
1975	8	113.2	1.0	112	+ 1.2	7.5
1976	8	119.6	1.0	118	+ 1.6	6.5

N	n	V_c °C	s_V °C	V_R °C	d °C	s_T in 10^{-3} °C
1980	8	117.5	0.9	115	+ 2.5	5.4
1981	8	114.4	0.95	116	— 1.6	5.4
1982	8	125.2	0.4	128	— 2.8	2.1
1983	8	120.4	0.6	121	— 0.6	3.2
1984	8	112.9	0.7	112	+ 0.9	4.0
1977	8	121.0	0.55	124	— 3.0	3.0
C. The unprotected thermometers with a scale from 0 to 30 °C.						
1885	12	205.4	0.55	217	— 11.6	4.3
1887	12	207.1	0.45	209	— 1.9	3.6
1888	12	208.8	0.55	212	— 3.2	4.5
1889	12	200.2	0.7	218	— 17.8	5.9
1890	12	213.2	0.8	181	+ 32.2	7.7
D. The unprotected thermometers with a scale from 0 to 60 °C.						
1891	12	195.8	0.8	193	+ 2.8	6.7
1893	10	196.9	1.0	201	— 4.1	7.7
1894	12	193.6	1.0	195	— 1.4	8.3
1895	12	208.8	0.5	207	+ 1.8	3.8
1897	14	234.2	1.0	234	+ 0.2	8.6

F. Determination of zero point corrections.

Here, as in so many other respects we used the methods originally devised by the Meteor Expedition [1]). The thermometers, 8 to 10 at a time, were placed in a vessel filled with shavings of ice specially frozen from destilled water. When after about half an hour temperature equilibrium has been established the vessel is reversed with thermometers and all and opened at the other end; one by one the thermometers are lifted till the zero point is just visible above the surface of the ice and then at once read off. If possible the readings may be repeated two or three times.

The vessel used for the purpose is a cylinder 22 cm in diameter and 45 cm high fitted with a lid at both ends and mounted in an iron frame on a horizontal axis so as to be easily reversible. The lids are of conical shape with a hole in the centre to let meltwater flow away. To reduce heat losses both the vessel and the lids are double walled and in addition coated with a layer of felt 1 cm thick.

In the tropics the ice melts very rapidly so that a large supply is required. Moreover only one single reading can be made the second reading being, as Böhnecke experienced, spoilt by the high temperature of the air. It was therefore a great convenience that the managing directors of the Experimental Station of the Java Sugar Industry offered us the use of their cold chambers. There in a room at about 10 °C we could make the observations at our ease and with accuracy while a second chamber at — 2 °C was made use of to store away our fresh supply of ice. Since the observations could be carried out so much more easily in Pasoeroean than elsewhere we restricted our determinations to the three occasions we had to go there with our instruments; that was in June 1929 before the expedition started, and in January and August 1930 when we returned to Soerabaja to have the ship overhauled.

Since at the temperatures at which the $^1/_{10}$ °C thermometers are used it is not necessary to aim at the very highest accuracy the zero points for these instruments which were only once determined (June 1929) will be omitted here. For the $^1/_{20}$ °C thermometers the zero point corrections, that is the zero point reading with sign reversed, have been compiled in table 15. The data for October 1928 were those observed at the P.T.R. in Berlin when the instruments were calibrated.

[1]) G. Böhnecke. Meteor Reports Vol. IV. Part. I. p. 219.

TABLE 15. Zero-point corrections for $^{1}/_{20}$ °C thermometers in °C.

Therm. No.	Oct. 1928	June 1929	Jan. 1930	Aug. 1930
	Thermometers from — 2 to + 8° C			
1656	+ 0.01	+ 0.005	0.00	0.00
1854	+ 0.01	— 0.005	— 0.005	
1855	+ 0.01	0.00	0.00	0.00
1856	+ 0.02	+ 0.02	+ 0.01	0.00
1857	+ 0.01	— 0.005	— 0.005	0.00
1858	+ 0.01	— 0.005	0.00	— 0.01
1859	+ 0.01	+ 0.01	0.00	0.00
1861	0.00	0.00	0.00	0.00
1862	+ 0.01	0.00	0.00	— 0.015
1872	0.00	+ 0.01	+ 0.005	0.00
1905	+ 0.02	+ 0.03	+ 0.01	+ 0.005
1906	0.00	+ 0.005	0.00	— 0.005
1907	+ 0.01	+ 0.005	— 0.005	
1908	+ 0.02	+ 0.015	0.00	+ 0.005
1909	+ 0.02	+ 0.015	0.00	0.00
1910	+ 0.01	+ 0.01	0.00	0.00
1911	+ 0.02	+ 0.01	0.00	0.00
1914	+ 0.02	+ 0.015		
1915	+ 0.01	+ 0.005	0.00	0.00
1916	+ 0.02	+ 0.005	0.00	0.00
1917	+ 0.01	+ 0.005	0.00	
1961	— 0.01	— 0.015	— 0.015	— 0.02
1962	0.00	— 0.015	— 0.02	— 0.03
	Thermometers from + 3 to + 13 °C.			
1651	+ 0.01	+ 0.01	+ 0.01	0.00
1874	+ 0.02	+ 0.01	+ 0.01	+ 0.005
1875	+ 0.02	+ 0.015	+ 0.01	+ 0.005
1876	+ 0.01	— 0.005	0.00	— 0.005
1877	+ 0.02	+ 0.02	+ 0.01	+ 0.015
1878	+ 0.03	+ 0.025	+ 0.02	
1880	+ 0.02	+ 0.005	0.00	0.00
1881	+ 0.01	+ 0.005	+ 0.005	+ 0.005
1882	+ 0.02	+ 0.015	+ 0.01	+ 0.005
1920	+ 0.01	+ 0.015	0.00	0.00
1921	0.00	+ 0.005	— 0.005	— 0.01
1922	+ 0.02	+ 0.015	+ 0.005	0.00
1923	+ 0.01	+ 0.01	0.00	— 0.005
1924	+ 0.01	+ 0.005	0.00	0.00
1925	0.00	0.00	0.00	
1926	0.00	+ 0.01	0.00	0.00
1927	+ 0.01	+ 0.005	0.00	0.00
1928	+ 0.01	+ 0.01	0.00	0.00
1929	0.00	— 0.01	— 0.01	0.00

Each entry in this table is the average of several independent determinations, from which standard errors were also computed for every single instrument, these being combined into a final error by the methods which have been sufficiently explained before. The results are given in table 16.

TABLE 16. Standard errors of the zero-point determinations for $^1/_{20}$ °C thermometers.

	June 1929	January 1930	August 1930
Average number of determinations for each thermometer	$2^1/_2$	3	4
Standard error of a single determination	0.004 °C	0.0025 °C	0.0025 °C
Standard error of final result. . . .	0.003 °C	0.0015 °C	0.0012 °C

The determinations in June 1929 were less accurate than the later ones chiefly, I think, owing to a lack of experience during the first experiments. The accuracy reached in January and August 1930 is quite satisfactory; the error of a single observation is even slightly less than the reading errors derived from the V determinations (see page 26) This is easily explained as in the present instance. a single determination is the average of at least two different readings. From the errors in table 16 it may on the other hand be deduced that errors in the breaking off of the thread of mercury must be negligibly small; Böhnecke came to the same conclusion.

As mentioned earlier the thermometers were given 30 minutes to acclimatize to the temperature of the melting ice. Frequently we noted, however, that when the instruments on being inserted in the ice had a temperature of 25 to 30 °C the first measurement would give a reading 0.02 to 0.03 °C higher than the subsequent determinations. Presumably the thermometers had not cooled down completely even after half an hour. In such cases the first observation was rejected.

During the experiment the melting temperature of the ice was checked with two standard thermometers specially bought for this purpose but deviations from zero exceeding the possible reading errors were never observed.

On the average our results agree with the observations of the Meteor. The greater part of our instruments show a gradual decrease of the zero point correction corresponding to a slight contraction of the mercury reservoir; some thermometers, however, first start with an increase which is afterwards followed by a normal decrease.

TABLE 17. Frequency of changes in the zero-point corrections of the $^1/_{20}$ °C thermometers.

Change	Frequencies.		
	October 1928 to June 1929	June 1929 to January 1930	January 1930 to August 1930
— 0.02	0	1	0
— 0.015	6	3	1
— 0.010	6	12	4
— 0.005	15	12	11
0.000	9	11	16
+ 0.005	3	2	3
+ 0.01	3	0	1
+ 0.015	0	0	0
Average Change	— 0.004^3	— 0.005^7	— 0.002^3
Standard deviation from average	0.007	0.005^5	0.005

In table 17 we have entered the frequencies of the changes in the zero point corrections observed in the different periods. From June 1929 to January 1930 the changes are found to be slightly greater

than from October 1928 to June 1929, but in the interval from January to August 1930 they have sensibly diminished. On the whole the changes seem to have lasted somewhat longer on board Snellius than on board Meteor for Böhnecke reports that his instruments showed appreciable variations of their zero points only during 4 to 8 months after their date of manufacture.

From January to August 1930 thermometer 1862 altered its zero point by — 0,015 °C by that time an abnormally high amount; in September of the same year this instrument refused to register at all, the thread of mercury did not break off any more. It is very likely that both facts are due to some damage to the breaking off constriction of this thermometer. This was, however, the only irregularity which we observed and abnormal changes of 0,03 to 0,08 °C as found by Böhnecke for some of his instruments did not occur in our case. This again confirms the conclusion drawn on page 19 that we have been more fortunate with respect to the homogeneous quality of our thermometers.

As stated before interpolations between the zero point determinations were not made; the corrections for June 1929 were applied until new observations were made in January 1930 and so on. From table 17 it will readily be seen what inaccuracies in our observations have been the result of this. From June 1929 to January 1930 for instance the average change in the correction was 0,006 °C and the mean square deviation from this average is 0,0055 °C. Hence the temperature observations at the end of this period will have been too high by 0,006 °C on the average and they were subject to a partial error with a standard value of 0,0055 °C. Being zero at the outset they gradually increased to these amounts being then reduced again to zero by the determinations of January 1930.

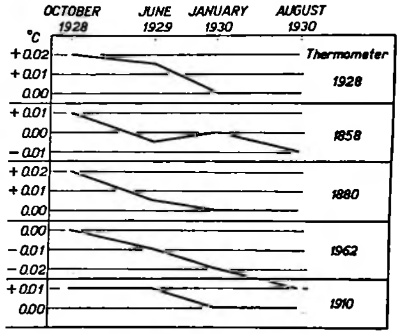

Fig. 18. Zero point corrections for some of our instruments.

In figure 18 the zero point corrections for some of our thermometers have been plotted to illustrate their general behaviour.

§ 6. THE UNPROTECTED REVERSING THERMOMETERS AND THE DETERMINATION OF THE DEPTH OF OBSERVATION

The unprotected reversing thermometer is essentially of the same construction as the protected one. Only the glass envelope protecting the instrument is open at one end so that the thermometer is subjected to the pressure prevailing in the sea. By the ensuing compression the reading becomes higher than that of a protected thermometer and from the difference the pressure and consequently the depth of reversal can be computed.

Again we used the same pattern of instruments as developed on behalf of the Meteor a description of which will be found in the reports of that expedition [1]).

We took with us

6 thermometers ranging from 0—30 °C, graded in $^1/_{10}$ °C

and 6 thermometers ranging from 0—60 °C, graded in $^1/_5$ °C

One of the 0—30 °C instruments was obtained from the firm Franz Schmidt in Berlin; on the whole this thermometer fulfilled its purpose equally well as the other instruments which were all made by Richter and Wiese.

As a rule two unprotected thermometers were used with every series of observations whereas from station 104 onwards we also used an unprotected instrument with the wire sounding so as to gave an independent check on the depth of the bottom. As was to be expected this occasioned the loss of some instruments so that towards the end of the expedition two more thermometers with a scale from 0—60 °C were ordered which increased our total stock of this type from 6 to 8.

The unprotected thermometers were used in the same manner as the protected instruments (see page 16). The corrections were calculated by slide rule.

[1]) Meteor Reports Vol. IV. Part. I. p. 60 ff.

As has been shown by Wüst in the Meteor Reports in calculating the depth from the reading of the unprotected thermometer, we may use the same average density (which is a function of the depth) over such a wide area as that traversed by the Meteor expedition. This will therefore hold as well in the more limited region in which our work was carried out. We calculated the density for 5 different stations and used the average of these in computing the depths of our observations. The densities adopted have been entered in table 18.

TABLE 18. Average densities $\rho_m = \frac{1}{D} \times \int_0^D \rho(z) \, . \, dz$ used in calculating the depth from the indications of the unprotected thermometers.

Depth in M	Density	Depth in M	Density	Depth in M	Density
100	1,0230	600	1,0271	3000	1,0340
200	1,0243	800	1,0280	4000	1,0365
300	1,0252	1000	1,0287	5000	1,0391
400	1,0260	1600	1,0302		
500	1,0266	2000	1,0315		

General behaviour of the instruments

With the serial observations about 1500 depth determinations were carried out. Of these 64, that is 4.3% had to be discarded as definitely or probably erroneous while 13 observations (0,9%) were lost owing to a failure of the thermometers. These failures were twofold; in some cases the mercury broke off at a point P near the main reservoir as indicated in fig. 19, and in others the discrepancy between the length of wire paid out and the depth indicated by the unprotected thermometer was far too large (more than 100 M) to be accepted.

In the 64 erroneous observations the differences between thermometric depth and length of wire were smaller, mostly about 20 M. To decide whether we had to do with an error or whether the discrepancy was due to the incline of the wire the following principles were used. If the thermometric depth exceeded the length of wire by 20 M or so there could be no doubt that the indications of the thermometer were in error. Again if in one set of observations two unprotected thermometers used in 150 and 400 M indicate respectively 130 and 398 M it is almost certain that the instrument in 150 M gave a wrong reading. Finally in dubious cases a comparison with other stations in the same neighbourhood sometimes assisted in forming a decision. For if the observations are made under favourable weather conditions a large difference between length of wire and thermometric depth is hardly acceptable unless similar discrepancies have been observed at other stations near by. As a matter of fact during our expedition large differences were mainly met with in certain regions especially in some straights; in this respect we mention for instance Stations 30 to 39 in the straight of Makasser, stations 271 to 273 north of Halmaheira and stations 293 to 300 lying in two straights south of Mindanao. In the central parts of the deep sea basins on the other hand the differences were hardly ever more than 1% of the depth.

On one occasion the deviations were so extreme that they merit to be separately mentioned. At station 299 in the straight of Kawio, south of Mindanao, observations were made down to 1200 M. The ship was manoeuvred so that all the time the wire at the surface stood nearly vertical. Nevertheless two unprotected thermometers placed on the wire at 800 and 1200 M recorded depths of 544 and 814 respectively M. This result was at first ascribed to some serious mishap and the series was therefore repeated this time with three unprotected thermometers.

Fig. 19. Defect of the unprotected reversing thermometer.

[1]) Vol. IV. Part. I. pag. 00.

We now observed

Thermometric depth	Length of Wire
408 M	500 M
609 M	800 M
914 M	1200 M

the deviations being hardly less extreme than in the first set. Compass bearings on islands close by proved that the ship was drifting with great speed. The currents must evidently have been very strong and varying in direction to cause such deviations while the wire at the surface stood vertical.

Accuracy

Meteor investigations have brought to light that the pressure coefficient of unprotected reversing thermometers undergoes slight changes in the course of time. Wüst [1]) even recommends that large expeditions should be equipped with apparatuses which permit repeated determinations of the pressure coefficient from time to time. Very much the same purpose can, however, be reached by simpler methods. The deep sea itself provides an ideal hydrostatic press, so that by lowering a number of unprotected instruments to the same depth we may check them against each other at any time and at any pressure. From such observations corrections can be computed which will reduce the pressure coefficients of all our instruments so that they mutually agree. If now and again one or two thermometers are send back to be retested at the P.T.R. this will fix the absolute value of the pressure coefficient as well. On the average, however, the changes are so small that it seems questionable whether this is necessary.

We realised the advisability of experiments of this nature too late so that only a small number of observations have been carried out towards the end of our expedition. These have been compiled in table 19.

TABLE 19. Observations with two or more unprotected thermometers in the same depth.

Station	Therm. No.	Therm. depth in M	Average in M	d in M	Standard error in M	Wiredepth in M
A. Serial observations with one of the great winches.						
	1888	390		—2		
374	1889	388	392	—4	5	400
	2327	398		+6		
39A	1890	545	546	—1	1.5	550
	1889	547		+1		
39A	1890	564	564	0	1	575
	1889	563		—1		
	1885	799		—4		
	2496	806		+3		
372	2495	805	803	+2	3	800
	1895	801		—2		
	1888	803		0		
	1888	991		+4		
378	1889	982	987	—5	4.5	1000
	2327	987		0		
	1885	1475		—6		
	2496	1485		+4		
374	2495	1480	1481	—1	4.5	1500
	1895	1478		—3		
	1897	1486		+5		

[1]) Meteor Reports Vol. IV. Part. I. p. 68.

TABLE 19. Continued.

Station	Therm. No.	Therm. depth in M	Average in M	d in M	Standard error in M	Wiredepth in M
236	1894 1895 1893	1997 1997 1997	1997	0 0 0	0	2000
374	2495 2496 1895	2506 2512 2506	2508	— 2 + 4 — 2	3.5	2540
232	1894 1895 1893	4496 4490 4489	4492	+ 4 — 2 — 3	4	4500
B. Observations made with wire soundings.						
381	2496 1895	1010 1015	1012	— 2 + 3	4	
239	1893 1894	1226 1239	1232	— 6 + 7	9	
380	2496 1895	2395 2382	2388	+ 7 — 6	9	
373	2496 1895	2695 2685	2690	+ 5 — 5	7	
236	1893 1894	3586 3601	3594	— 8 + 7	11	

The standard error of a single observation computed by equation (10) of page 13 have been entered in columm 6; they embody the errors to which the depth determinations are liable. If however the pressure coefficient of our thermometers had changed considerably during the course of the expedition we should expect the standard error to increase with the depth. As table 19 does not show a conspicuous effect of this kind we may conclude that errors in the pressure coefficients have not seriously affected our material. This is further substantiated by the good agreement of the indications of thermometers No. 2495 and 2496 with those of the other instruments; for these were the instruments that were received towards the end of the expedition and had then quite recently been tested at the P.T.R.

Combining the standard errors in column 6 into one single estimate as explained on page 13 we obtain a standard error of 3 M, a very satisfactory result. Further on (page 40) it will be shown that, in our case at least, an error of this order in the depth is negligible in comparison with the other errors in the temperature observations. At small depths the uncertainty due to internal waves is by far the most serious source of error and at great depths the accuracy is limited by the errors of the protected thermometers the temperature gradient being so small that errors in the depth are rendered unimportant.

Whenever the difference between thermometric depth and length of wire is small the latter can conveniently be adopted as the correct depth of observation. But if the deviations are more pronounced corrections must be made. In this respect we have adhered to the following rules which are more or less arbitrary.

At depths less than 400 M a correction has been applied whenever the difference between wire length and thermometric depth amounted to more than 5 M. Between 400 and 1000 M a correction was made when the difference exceeded 1% of the depth, and below 1000 M when the difference was greater than 10 M. At depth where no unprotected thermometer had been used the correction was computed by linear inter- or extrapolation.

This interpolation will introduce an extra error so that the standard error of 3 M derived from

table 19 will be on the low side if all our observations are considered, and not only those in which an unprotected thermometer has been employed. An estimate of the error in an interpolated depth can be obtained in the following way.

In our serial observations we used as a rule two unprotected thermometers in each series at different depths. From the depth recorded by the lowest instrument we may interpolate the depth of the higher instrument and compare the value thus found with that actually observed. This has been done by computing the root mean square difference $s = \sqrt{\frac{\Sigma(D - D')^2}{n}}$ between the two values. The results are given in table 20.

TABLE 20. Comparison of interpolated and observed depths.

Series	Length of wire at which the unp. therm. were attached	Standard difference at 150 M	Number of obeservations
1	150 and 400 M	4,7 M	317 all stations
		4,0 M	313 only
2	800 and 1500 M	5,6 M	179 all stations except 299
		4,3 M	162 only

In the first series the standard difference calculated from all our data is strongly influenced by four very bad results; if these are cancelled the value 4.7 M reduces to 4.0 M. In the second series station 299 which is the extreme example mentioned on page 33 has not been taken into account.

As we should expect the standard difference is somewhat greater in the second than in the first series; moreover it is not so strongly influenced by some bad results though still if about 10% of the data are disregarded the difference is reduced from 5,6 to 4,3 M. But even if we consider all our observations the resulting standard differences are not high and they furnish additional evidence of the accuracy of the unprotected thermometers.

The values in table 20 can be analysed a little further as we will illustrate in the case of the second series. The sources which contribute to the standard differences are

1. The standard error in the depth observed at 800 M which amounts to 3 M (see page 34).
2. The standard error in the depth observed at 1500 M which, however, by the interpolation is reduced to

$$^{8}/_{15} \times 3\text{ M} = 1{,}6\text{ M}$$

3. Errors introduced by the linear interpolation which can now be estimated by the principles of § 4. Their partial standard error will be represented by

$$s_i^2 = 5{,}6^2 - 3{,}0^2 - 1{,}6^2 = 19{,}4\text{ M}^2$$

$$\text{or } s_i = 4{,}4\text{ M}$$

The value 4.4 M thus obtained represents the errors made in interpolating the depth at 800 M between the surface and the depth recorded in 1500 M. If as was actually done in practice we interpolate separately between 0 and 800 M and between 800 and 1500 M the errors will be about half as large, or 2.2 M. With the standard error of 3 M in the indications of the unprotected thermometers this will give a total error of $\sqrt{3^2 + 2.2^2} = 3.6$ M so that if we set the general error of our depth determinations at

4 Meters

this will rather be too large than too small. To what measure this error influences the reliability of our observations will be discussed in detail on page 37.

Note on the calculation of the depth

To calculate the depth the following formula is generally used.

$$D. = \frac{10 . \Delta T}{a . \rho_m} \tag{1}$$

where ΔT is the difference between the readings of unprotected and protected thermometers, a is the pressure coefficient in °C per KG/cm^2 and ρ_m is the average density of the sea water defined by

$$\rho_m = \frac{1}{D}\int_0^D \rho(z) \, . \, dz$$

$\rho(z)$ being the density at the depth z; to calculate ρ_m and exact knowledge of the depths of observation is not required since ρ_m can be approximated with sufficient accuracy by assuming the depth to be equal to the length of wire paid out.

Perhaps it is worth mentioning that equation (1) is not entirely correct though the error in it is not of great consequence.

Equation (1) is based on the assumption that the hydrostatic pressure in KG/M at a depth of D meters is represented by

$$P = \frac{1}{10}\int_0^D \rho(z) \, . \, dz = \frac{1}{10} \rho_m \, . \, D \tag{2}$$

whereas in reality this pressure is given by

$$P = \frac{1}{10 \, . \, g_0}\int_0^D g(\rho, z) \, . \, \rho(z) \, . \, dz \tag{3}$$

where $g(\varphi, z)$ is the gravitational force at latitude φ and depth z, g_0 being the same force at 45° and at the surface of the earth.

Now we have

$$g(\varphi, z) = g_0 \, . \, (1 - 2{,}64 \, . \, 10^{-3} \cos 2\varphi + 2{,}25 \, . \, 10^{-7} z) \; ^{1)} \tag{4}$$

Inserting this in equation (3) and carrying out the integration we obtain

$$P = \frac{1}{10} (\rho_m \, . \, D - 2{,}64 \, . \, 10^{-3} \, . \, D \, . \cos 2\varphi + 1{,}13 \, . \, 10^{-7} \, . \, D^2) \tag{5}$$

where in calculating the second and third term on the right hand side we have put $\rho(z) = 1$, which signifies that second order corrections have been cancelled.

From equation (5) we have

$$D = \frac{10 \, . \, \Delta T}{a \, . \, \rho_m} + c(\varphi, D) \tag{6}$$

where $c(\varphi, D)$ is a small correction which is represented by

$$c(\varphi \, . \, D) = 2{,}64 \, . \, 10^{-3} \, . \, D \, . \cos 2\varphi - 1{,}13 \, . \, 10^{-7} \, . \, D^2 \tag{7}$$

In computing $c(\varphi, D)$ we may take for D some approximate value. For various depths and latitudes the necessary corrections are given in table 21.

TABLE 21. Corrections $c(\varphi, D)$ to be applied to formula (1)

D	$\varphi = 0°$	45°	90°
1000	2,5 M	— 0,1 M	— 2,7 M
2000	4,8	— 0,4	— 5,7
3000	6,9	— 1,0	— 8,9
4000	8,8	— 1,8	— 12,4
5000	10,4	— 2,8	— 16,0

We see that the corrections are small, so small in fact that they will in most cases be perfectly negligible, so that the point here discussed is only of theoretical interest.

In our own case the necessity of these extra corrections was realised only after the work on our

[1]) See for instance A. Defant. Dynamische Oceanographie. Berlin 1929 p. 5.

observations was well on its way and we did not think the corrections of sufficient importance to warrant a complete revision of our tables. Hence they have not been applied.

§ 7. COMPARSION OF THE DIFFERENT SOURCES OF ERROR AND THEIR INFLUENCE OE THE INTERPRETATION OF OUR TEMPERATURE OBSERVATIONS

The sources of error in the temperature observations are

1. The errors of the thermometers.
2. The errors in the depths.
3. Errors due to the variations caused by internal waves.
4. Errors in the position of our stations.

We will now compare these various errors and their relative influence on the accuracy of our observations.

1. The errors of the protected reversing thermometers have been abundantly discussed in § 5; they are represented by a standard error

$s_1 = 8.9 \times 10^{-3}$ °C for the $^1/_{20}$ °C thermometers.
and $s_1 = 10.7 \times 10^{-3}$ °C for the $^1/_{10}$ °C thermometers.

2. The standard error in the depth has been dealt with in § 6 (page 35); we there arrived at a final value of 4 M independent of the depth of observation. The corresponding error in the temperature is obtained by multiplying the error in the depth by the temperature gradient. For this purpose the average temperature gradient for various parts of the region visited by the Snellius were computed. These have been collected in table 22.

TABLE 22. Average vertical temperature gradients in different regions.

Depth in M	Celebes Sea	West Banda Sea	Pacific Ocean	Indian Ocean	Average	
Gradients per Meter in 10^{-3} °C						
50	45	40	65	70	55	
100	95	115	105	80	99	
150	80	90	70	85	81	
200	60	62	45	50	54	
250	45	40	35	42	41	
300	30	27	30	23	28	
400	16	13	21	14	16	
500	9	10	10	9	9.5	
600	7,5	9	7	8	8	
800	6	6	6	6	6	
					A	B
1000	3	3	4	4	3	4
1500	0,6	1,2	2,3	2,5	0,9	2,4
2000	0,14	0,56	1,2	1,3	0,35	1,3
2500	0,00	0,26	0,63	0,77	0,13	0,70
3000	— 0,06	0,00	0,20	0,56	— 0,03	0,38
3500	— 0,10	— 0,07	0,00	0,48	— 0,09	0,25
4000	— 0,12	— 0,10	— 0,08	0,18	— 0,11	0,05

Column 6A gives the average of Celebes and Banda Sea, column 6B the average of Pacific and Indian Ocean·

Stations used:
Celebes Sea St. 46—58, 73—77, and 301—305.
West Banda Sea St. 164 and 201—218.
Pacific Ocan St. 262—265, 269—276, and 287—288.
Indian Ocean St. 130—132, 141—147, and 382.

Above 800 M the deviations between the different regions are small so that we may safely use the total average recorded in column 6 for all our observations. Multiplication with 4 M yields the temperature errors entered in table 25 column 4.

Below 800 M a distinction must be made between the deep sea basins of the Indian Archipelago and the regions of the Indian and Pacific Oceans; inside the archipelago the temperature gradients are smaller owing to the influence of the sills which separate the basins from the oceans. The average gradients for the basins and the oceans have been given separately in column 6 under A and B respectively. In table 25 the corresponding temperature errors have been similarly distinguished.

3. The errors caused by internal waves can be calculated from the repeated observations at the anchor stations (formula (10) page 13) Moreover, however, at numerous stations the first series of observations down to 400 M (series 1) was repeated at the end of the station (series 1A). From these repeated observations the standard error can be separately estimated by formula (12) of § 4. The various data computed from our material have been compiled in table 23.

TABLE 23. Standard errors in °C due to internal waves computed from various data.

Depth M	St. 39A	St. 135A	St. 253A	St. 308A	Anchor stations combined	Series 1 and 1A	Final Value	Vert. Displ. in M
50	0,65	0,35	0,9	0,25	0,55	0,45	0,5	9.1
100	0,55	1,3	1,3	1,5	1,3	0,95	1,15	11,5
150	1,3	0,65	1,0	1,9	1,4	1,0	1,2	15
200	1,4	0,5	1,15	0,5	0,9	0,7	0,8	15
250	0,9	0,4	0,8	0,35	0,6	0,55	0,6	14,5
300	0,7	0,35	0,5	0,6	0,55	0,4	0,5	18
400	0,45	0,2	0,4	0,45	0,4	0,4	0,4	25
500	0,27		0,4		0,35		0,35	33
600				0,25	0,25		0,25	31
800			0,12		0,12		0,12	20
Degr. of fr.	12	13	13	27	65	58	123	

In the last line we have entered the degrees of freedom (see § 4 p. 14).

The standard errors found at the anchor stations are all of the same order of magnitude though the depths at which the maximum variations were observed seem to have been somewhat different. By comparing the errors at different stations by the more critical statistical methods referred to on page 14 it was found that the differences are not large enough to be considered significant; the variations resulting from internal waves are of same order of magnitude over the entire region investigated.

In column 6 the errors found at the anchor stations have been combined by equation (11) of page 13; the resulting values agree in a satisfactory manner with those computed from the repeated serial observations which are recorded in the seventh column. The final standard errors given in column 8 have again been computed by the formula mentioned.

We have made no observations fromwhich the errors due to internal waves can be computed below 800 M. For a complete discussion of the accuracy of our data it is, however, of interest to endeavour an extrapolation of table 23 to greater depth which may be done on the basis of our present knowledge of internal waves. A theory of such waves in a sea with continuously varying density has been developed by J. E. Fjeldstadt [1]).

The main seat of the interval waves lies in the layers below the surface where the density changes rapidly with the depth. At greater depth the density can be considered as substantially constant and in that case the amplitude of the internal waves is according to Fjeldstadt's theory al inear

[1]) J. E. Fjeldstadt Geofysiske Publikasjoner 10 No. 6, 1933.

function of the depth. Since moreover the vertical amplitude will be zero at the bottom the vertical displacement will be proportional to the distance from the bottom.

If we divide the standard errors (table 23 column 8) by the temperature gradient (table 22) we find the standard vertical displacement, which has been entered in the last column of table 23. From 400 to 800 M this displacement is of the order of 25 to 30 M varying somewhat irregularly [1]).

On the basis of these facts we will therefore assume (for the purpose of extrapolating table 23 to greater depths) a standard vertical displacement of 30 M in 1000 M depth and of 0 M at the bottom the values between these being found by linear interpolation. This will give us a displacement which varies with the depth of the bottom but as it is not desirable to go too far in details we have carried out the computations only for a depth of 5000 M.

From the vertical displacement we obtain the temperature error by multiplying into the difference of the observed temperature gradient minus the adiabatic gradient. Between 0 and 2000 M the correction for the adiabatic changes in temperature is perfectly negligible but in the deap sea basins of the Indian archiplago where the adiabatic gradient prevails near the bottom it should be taken into account.

For the various parts of the region investigated by the Snellius the adiabatic gradients were computed from Ekman's tables [2]). There exists a slight difference between the oceans and the deap sea basins inside the archipelago, but between the various basins the differences are so small that they can be neglected. The requisite data have been collected in table 24. From them the standard errors of internal waves given in table 25 for depths exceeding 1000 M have been computed.

TABLE 24. Data used in extrapolating the errors caused by internal waves to depth exceeding 1000 M.

Depth in M	Temp. grad. in 10^{-3} °C/M		Adiab. grad. 10^{-3} °C/M		Difference 10^{-3} °C/M		Standard displace-ment in M
	Basins	Oceans	Oceans	Basins	Basins	Oceans	
1000							30
1500	0,9	2,4	— 0,093	— 0,089	0,99	2,5	26
2000	0,35	1,25	— 0,100	— 0,094	0,45	1,34	22
2500	0,13	0,70	— 0,108	— 0,099	0,24	0,80	19
3000	— 0,03	0,24	— 0,116	— 0,104	0,07	0,48	15
4000	— 0,11	0,05	— 0,131	— 0,120	0,02	0,07	8

It is of course open to question how far the variations due to internal waves can actually be considered as accidental errors and whether there is any sense in using the methods of § 4 in this instance. If we take a set of stations at moments which are in some degree dictated by chance and stand in no particular relation to the phase of the internal waves the resulting temperature variations will be purely accidental. But at the anchor stations where the observations were made at regular intervals these conditions are not satisfied. To compute the standard errors we should rather have taken our observations at irregular moments prescribed by chance. However, this may be, the results computed above can not be far amiss and since an estimate is all that can be obtained there is no point in insisting on complete validity of the formulae adopted. Since we have consistently treated our observations by the methods explained in § 4 we have also used these methods in this case.

4. By multiplying the error in the position of the vessel into the horizontal temperature gradient we find the corresponding error in the temperature observation. The horizontal gradients, however, computed from observations at stations in the same region are subject to very serious errors owing to the errors caused by internal waves. A more precise analysis of our data given below shows that the true temperature differences between the stations have been comparatively small so that the hori-

[1]) It is not excluded that these irregularities are real since theoretically the internal waves consist of the superposition of waves of the first, second, etc. order in which the maximum amplitudes occur at different depth. This point, however, is not relevant to our present purpose.
[2]) V. W. Ekman Ann. Hydr. Marit. Meteor 42, 342, 1914.

zontal temperature gradients have been small too; hence the effect of errors in the ships position will be negligible in comparison with the other error sources, and since they cannot be estimated by simple and straightforward methods we will not take them into account any further.

TABLE 25. Comparing the partial standard errors in the temperature observations due to different sources.

Standard error in °C due to

Depth in M	Instru-ments s_1	Intern. waves s_2	Depth determ. s_3	Total error s
50	0,011	0,50	0,25	0,56
100	0,011	1,15	0,44	1,23
150	0,011	1,2	0,36	1,25
200	0,011	0,8	0,24	0,83
250	0,011	0,6	0,18	0,62
300	0,011	0,5	0,13	0,52
400	0,009	0,4	0,07	0,41
500	0,009	0,35	0,043	0,35
600	0,009	0,25	0,036	0,25
800	0,009	0,12	0.027	0,12
A. Basins inside the archipelago.				
1000	0,009	0,075	0,012	0,075
1500	0,009	0,026	0,004	0,028
2000	0,009	0,010	0,003	0,014
2500	0,009	0,005	0,000	0,010
3000	0,009	0,001	0,000	0,009
4000	0,009	0,000	0,000	0,009
B. Pacific and Indian Ocean.				
1000	0,009	0,10	0,018	0,10
1500	0,009	0,065	0,009	0,067
2000	0,009	0,029	0,006	0,031
2500	0,009	0,016	0.003	0,019
3000	0,009	0,007	0,002	0,012
4000	0,009	0,000	0,000	0,009

For depths exceeding 1000 M the errors due to internal waves have been extrapolated as explained in the text.

If now we compare numerically the various sources of error we arrive at the results recorded in table 25.

Down to about 2000 M the errors caused by internal waves predominate; only near the surface the errors in the depth reach a value of the same order of magnitude though they are never more than 50% of the former errors. If we calculate the total error ($s = \sqrt{s_1^2 + s_2^2 + s_3^2}$) as done in the last column it will be realised that the contribution of the inaccuracies in the depths is really of little importance.

At very great depths the temperature gradients become so small that the influence of internal waves is reduced below the errors due to our instruments. In the basins this occurs below 2000 M but in the oceans we have to go down below 3000 M to reach these conditions. In these abysmal regions the accuracy of our observations is substantially limited by the errors of the thermometers.

The error in the determination of the depth nowhere plays an important part.

It will of course be understood that table 25 is only a general estimate and cannot claim a high degree of accuracy. For instance the extrapolation made in column three may be of questionable value and has only been made for lack of more exact data suitable to our purposes.

Les uw now investigate in what measure the errors given in table 25 will interfere with the interpretation of our observations in horizontal or vertical charts. To this end we have computed the average temperatures and the standard deviations with respect to this average for sets of stations situated in various parts of the archipelago and for all our observations taken together (these last only down to 500 M). The results have been collected in table 26 to which the total errors from table 25 have once again been added column 7.

TABLE 26. Standard deviations in the temperature in °C for various parts of the archipelago and for the whole area visited by the Snellius.

Depth M	Celebes sea	West Banda sea	Pacific Ocean	Indian Ocean	Entire Area	Total error from table 25		Real variations $s_r^2=\sqrt{s_a^2-s_e^2}$
50	0,9	1,1	1,35	0,6	1,4	0,56		1,3
100	1,55	1,3	2,6	1,1	1,75	1,25		1,2
150	1,45	1,1	2,0	1,1	1,45	1,25		0,75
200	1,1	0,7	1,9	0,55	1,10	0,83		0,72
250	1,25	0,57	1,6	0,4		0,62		
300	1,23	0,44	1,4	0,4	0,87	0,52		0,70
400	0,55	0,40	0,65	0,21	0,54	0,41		0,35
500	0,39	0,34	0,45	0,24	0,44	0,35		0,27
600	0,39	0,33	0,30	0,19		0,25		
800	0,28	0,23	0,22	0,18		0,12		
						A Basins	B Oceans	
1000	0,14	0,12	0,16	0,11		0,075	0,10	
1500	0,04	0,06	0,085	0,06		0,028	0,067	
2000	0,014	0,025	0,055	0,04		0,014	0,031	
2500	0,006	0,021	0,045	0,03		0,010	0,019	
3000	0,009	0,015	0,033			0,009	0,012	
4000	0,008	0,018	0,008			0,009	0,009	

Stations used:
Celebes Sea St. 46—58, 73—77, and 301—305.
West Band Sea St. 164, and 201—218.
Pacific Ocean St. 262—265, 269—276, and 287—288.
Indian Ocean St. 130—132, 141—147, and 382.

The data in this table are worthy of a detailed discussion since they provide criteria for the value of our observations. Above 600 M the standard deviations between the stations are only slightly higher and in some instances even somewhat lower than the standard errors. This indicates that the temperature differences between the different stations are almost entirely due to errors, especially those resulting from internal waves. An exception can be made at 250 and 300 meters in the Celebes Sea and from 50 to 400 M in the Pacific Ocean where the standard deviations are about twice as large as the errors so that our observations indicate the existence of real temperature differences. Remarkably enough the standard deviations in the Indian Ocean are less than the errors, and it seems open to question whether the errors computed are really valid in this region.

At greater depths a distinction must be made between the basins and the oceans as has been done earlier. In the Celebes Sea the standard deviations are about equal to the errors but in the West Banda Sea they are systematically higher. In the latter region true temperature differences seem to exist down to 4000 M. The same holds for the Pacific Ocean down to 3000 M; at 4000 M which lies below the level of minimum temperature the differences have disappeared, standard deviation and standard error being equal.

The variations over the entire region represented in column 6 are somewhat greater than those in the enclosed basins but it is evident that this is mainly due to the large differences encountered in the Pacific Ocean. The standard deviations due to real temperature differences can be computed

TABLE 27. Standard errors computed from the Meteor anchor stations.

Station	147	176	186	197	214	229	241	254	288	Root Mean Square	Standard deviations from profile 8, 9, and 11.
Pos.	14°58′ S 0°7′ W	21°30′ S 11°43′ W	8°59′ S 10°54′E	8°43′ S 16°40′ W	3°32′ N 26°1′ W	2°27′ S 0°56′ W	3°50′ S 1°5′ E	2°27′ S 34°56′ W	12°38′ N 47°36′ W		
n	10	10	11—6	9	7—6	8	8	23	39		
Depth	Standard errors in °C										
0 M	0.19	0.072	0.33	0.092	0.115	0.13	0.22	0.21	0.059	0.18	2.0
25	0.084		1.44			0.23	1.88			1.19	2.3
50	1.15	0.024	0.23	0.016	0.018	1.18	0.42	0.070	0.019	0.54	3.75
75	0.36			0.11	0.85	0.29			0.23	0.45	4.6
100	0.82	0.029	0.12	0.77	1.70	0.13	0.094	1.28	0.61	0.83	4.35
150	0.19	0.52		0.42	0.83	0.048		0.53	0.51	0.50	2.75
200	0.18	0.47	0.17	0.164	0.15	0.12		0.078		0.36	1.60
300		0.23	0.21								0.95
400			0.11	0.12			0.245			0.17	0.67
600			0.086	0.091			0.086			0.088	0.57
800			0.038	0.56			0.077			0.059	
1000			0.018	0.022			0.028			0.023	
1200				0.0073			0.015			0.011	
1600				0.023			0.024				
2000				0.036			0.024				
2500				0.013			0.029				

n = number of observations from which the errors were computed.

from column 6 and 7 by the equation $s_r^2 = s_a^2 - s_c^2$ and in this manner the data entered in the last column have been obtained. The variations resulting from true temperature differences are of the same order of magnitude as those caused by internal waves.

It is instructive to compare our material with similar data computed from the Meteor observations [1]), which have been collected in table 27. At some depths observations have been carried out only at a few anchor stations; besides this considerable differences occur in the depths at which the internal variations reach their maximum and consequently the errors at one and the same depth vary between much wider limits than in the case of the Snellius (table 23). Hence the standard errors (root mean square) calculated in column 11 must be considered as very rough estimates only. Nevertheless the differences with the Snellius data are sufficiently marked to warrant some general conclusions.

As above we have to compare the standard errors of column 11 with the standard deviations between different stations. For the entire region crossed by the Meteor these deviations would of course be very large owing to the great variations in latitude of the oceanographic stations. In order to obtain data more directly comparable with the Snellius observations I have therefore computed the standard deviations from a set of stations lying between 10° N and 10° S latitude, for which I took the stations from profile VIII, IX, and XI. The results of these calculations have been compiled in column 12.

In fig. 20 the various data for Meteor and Snellius have been compared with each other. The two highest curves represent the standard deviations of column 6 and 12 in table 26 and 27 respectively; the Meteor shows higher values than the Snellius the differences being very pronounced down to

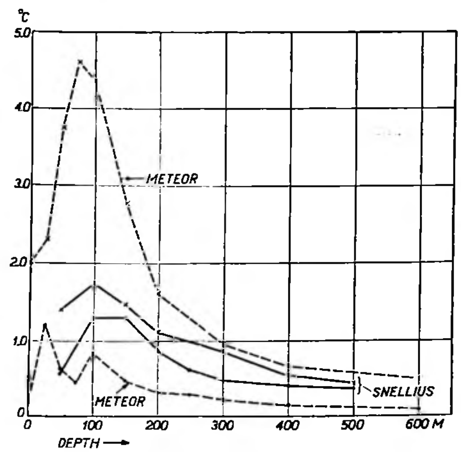

Fig. 20. Standard deviations and standard errors for Meteor and Snellius.

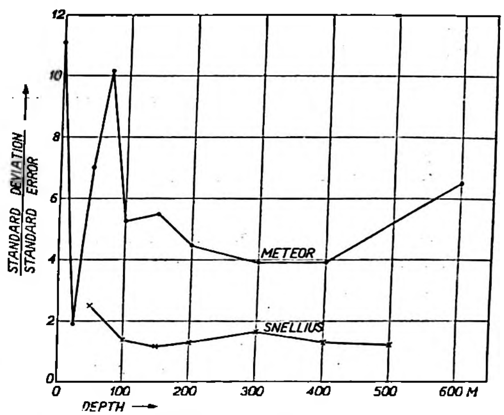

Fig. 21. Ratio of standard deoiation to standard error for Meteor and Snellius.

200 M depth. This is undoubtedly a consequence of the oceanic currents which cross the Meteor region and carry waters of very different origin within this area. In the East Indian Archipelago the enclosed seas are in a large measure cut off from the oceanic circulation so that the temperature varations are less.

The standard errors due to internal waves are plotted in the two lowest curves in fig. 20; they are over the entire range of depths two to three times as large for the Snellius than for the Meteor. Whether this is also a result of the special conditions prevailing in our basins is not so easily settled, so that we will not discuss the point here.

The disturbing influence of internal waves in the interpretation of our observations can best be discussed by the ratio of standard deviation to standard error a quantity which has been separately plotted in fig. 21. This ratio should be greater than unity a condtition actually satisfied. When, however, it is only slightly greater than 1 this shows that the temperature differences between different stations are for a large part due to the accidental errors introduced by the internal waves.

[1]) Vol. VII. Part. 1.

This is the case for the Snellius, the curve in fig. 21 never rising above 1.7 except at 50 M. The situation is entirely different for the Meteor where barring a value of 1.9 at 25 M (which may be due to a lack of a sufficient number of observations) the ratio between standard deviation and standard error is of the order 4 or even higher.

For stations where the observations have been repeated conditions will be more favourable, for by averaging both observations the error is reduced in the ratio $1 : \sqrt{2}$ and the ratio of fig. 21 will be increased by a corresponding factor. Nevertheless it is evident that in interpreting details of the temperature distribution we will have to be careful. A bend in an isotherm which is based on only one observation may be entirely due to an error, whereas in the case of the Meteor the same feature may confidently be accepted as indicating a real property of the oceanic circulation.

To what degree the errors will actually interfere with the interpretation of our temperature charts can only be settled by the final discussion of our observations.

Besides it should be noted that the features of an oceanic circulation are nearly always least conspicuous in the temperature distribution and this is the only factor which we have been discussing above. It is to be expected that if a similar analysis is carried out for salinity or oxygen content the errors will turn out to be less important.

In conclusion it may be noted that there is an obvious way by which the errors due to internal waves may be completely eliminated from our material. For if we plot the salinity against the temperature the curve obtained will evidently be independent of the internal displacement of the water masses. Nrom such a plot $S = f(t)$ we may read the salinity corresponding to some fixed temperature and these plotted in a horizontal map wil represent a feature of the oceanographic circulation which no longer depends on the internal waves. Wheter such charts are of value and how they must be interpreted will require a special investigation but the treatment proposed is closely analogous to the method of „anomalies" succesfully applied by Helland-Hansen and Nansen [1]) in their study of the Eastern North Atlantic.

§ 8. CURRENT METERS

We had

1. 1 Ekman Merz current meter for strong currents (10—250 cm/sec.) made by Marx and Bernt in Berlin.
2. 1 Ekman-Merz current meter for weak currents (3—150 cm/sec.) also from Marx and Bernt.
3. 2 Ekman repeating current meters complete with in addition
   2 compass boxes,
   2 calibrated propellers,
   100 safety messengers
   and a number of smaller spare parts.

A foto of the repeating current meter is reproduced in Plate II fig. 7.

Since the principles of these current meters are generally known they will only very briefly be mentioned here. Details will be found in the various original papers in which they were described [2]). Both instruments measure the current by counting the revolutions of a sensitive propeller in a given interval. After the instrument has been lowered to the desired depth two messengers are send down in succession. When the first messenger hits the current meter the counting dial is coupled with the axis of the propeller; by the second messenger which is dropped 5 or 10 minutes later the coupling is interrupted again so that the number of revolutions can be read off after the apparatus has been hauled on deck.

To record the direction of the current use is made of a compass box divided in 36 compartments above which a compass needle with a groove over its north pole is mounted. The clockwork while registering the revolutions of the propeller drops small bronze balls at regular intervals onto the

[1]) B. Helland-Hansen and F. Nansen. The Eastern North Atlantic. Geofysiske Publikasjoner Vol. IV. No. 2. 1926.

[2]) V. W. Ekman. Publ. de Circonstance No. 24 Copenhague 1905 A. Merz. Veröff. des Instituts für Meereskunde N. F. Reihe A No. 7 1921. Meteor Reports. Vol. IV. Part. I. p. 245 ff.

centre of the compass needle; these balls roll down the north pole falling at the end in one of the 36 compartments where it is afterwards found as an indicator of the direction of the current.

It is a drawback that the current meter must be drawn up after every observation which takes a long time especially at large depths. To avoid this the repeating current meter has been developed in which both the direction of the current and the reading of the dial are recorded by means of sets of three bronze balls which have been numbered so that the various records can afterwards be separated. With this apparatus about 30 observations can be made without hauling in. Use is made of messengers which upon hitting the instrument split into two halves which slide down a funnel and are collected in a bucket suspended underneath the current meter. (See Plate II Fig. 7).

The current meters were mainly in function at six anchor stations. At small depths the Ekman-Merz meters were used by means of a small hand winch placed as far as possible from the oceanographic winches from which the repeating current meter was manipulated. To keep the instruments in functioning order they were partly taken to pieces and carefully rinsed with fresh water at the conclusion of each anchor station, a measure which proved entirely effective.

The only real trouble we encountered was due to medusae which by sticking to the wire above the repeating current meter spoiled the observations. Down to 500 M the hitting of the messengers on the instrument could distinctly be heard by pressing the wire to the ear and in this way a regular check was possible. At greater depth, however, this method failed and now and again the greater part of a series of observations was lost in consequence of medusae, which was then only discovered when the series was finished and the apparatus brought on deck again.

When a messenger sticks on top of a medusa subsequent messengers hitting the first one will split in halves and be lost. To prevent this Professor Ekman designed safety messengers as indicated in fig. 22 which will be self explanatory. This arrangement, however, did not fulfill its purpose. For by the blow from the second messenger part H of the first one is vigorously knocked downwards into the elastic medusa; by inertia part K stays behind and is therefore lifted with respect to H which produces the loss of the messenger. Thus whereas formerly the first messenger was kept and the later ones lost, now the last messenger was retained on top of the medusa and the earlier ones had disappeared. All together 35 messengers were lost in one way or another.

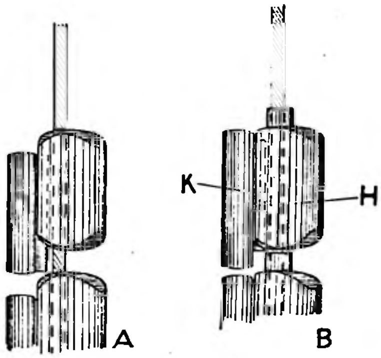

Fig. 22. Messengers for the repeating current meters. A = ordinary messenger; B = safety messenger.

At station 253A one of the repeating current meters was lost; a series of observations had been finished and the instrument had been drawn up untill only 15 M were left when suddenly the wire went slack and the current meter disappeared. The splice at the end of the wire had given way but to judge from what was left it had sustained greater forces than those resulting from the weight of the current meter with its appliances. Though persistent endeavours were made to formulate an acceptable hypothesis we have not been able to guess the real cause of this loss.

The observations were continued as soon as possible with the second instrument which, however, a little later was lowered too far so that the bucket for collecting the messengers got unhooked by touching the bottom. To remedy this second misfortune the funnel through which the messengers are guided into the bucket was closed at its lower end and used in stead of the bucket. By this contrivance a more limited number of observations could still be made in succession. Afterwards the instrumentmaker constructed a new bucket so that the current meter was complete again.

CHAPTER II

THE DETERMINATION OF CHLORINE AND OXYGEN CONTENT

by H. J. Hardon [1])

§ 1. The determination of the chlorine content of the sea water.
§ 2. The determination of the oxygen content of the sea water.

§ 1. THE DETERMINATION OF THE CHLORINE CONTENT OF THE SEAWATER

a. Inventary

Apart from the common apparatus requisite in a chemical laboratory our outfit for the chlorine titrations consisted of

14 Knudsen automatic burettes
18 Knudsen automatic pipettes
1000 bottles with patent stoppers for keeping the water samples
28 bottles of 200 cm^3
300 brown bottles of 100 cm^3

while we took with us the following reagents
55,5 KG nitrate of silver
400 tubes of standardised sea water
1 KG potassium chromate
together with a sufficient supply of potassium dichromate, sulfuric acid, nitric acid, ammonia and alcohol.

b. The determination of the chlorine content of the seawater

One of the most important properties of the seawater, its density, can be computed from the temperature and the salinity by which we designate the content of salts expressed in grams per 1000 grams of seawater. The salinity S is in its turn calculated by the simple relation

$$S = 0{,}030 + 1{,}805\ Cl$$

where Cl represents the chlorine content again in grams per 1000 gr. of seawater, and bromides being accounted for as an equivalent quantity of chlorides.

The determination of the chlorine content was carried out by the method developed by Mohr as early as 1856 which is simple and eminently suitable for accurate serial analysis. It is based on the reaction of the chlorides (and bromides) with silver nitrate giving insoluble silver halogenides. When all the chlorides have been precipitated a slight excess of silver nitrate yields a red coloured slightly soluble silver chromate with potassium chromate which is added as indicator.

[1]) When this chapter was finely prepared for the printer in 1941 some alterations and additions seemed desirable. Owing to the lack of communication Dr. Hardon could not be consulted concerning these changes so that they have been introduced without his consent.

Analysts. This simple titration does not call for the knowledge and experience of a skilled analyst. An accurate and reliable person will obtain excellent results after a little practice. It was therefore fortunate that some of the sailors of the Snellius could be told off for this work during the expedition; first Class Sailor Marquart obtained a short preliminary training at den Helder under the supervision of Ir. Liebert, whereas the First Class Sailor Wassenaar and the Second Class Sailors Onkenhout and Louws acquired the necessary routine during the trial trip in the Atlantic and the voyage to the Netherlands East Indies.

Accomodation. On the boat deck near the stern between the cabins of biologist and geologist a small chemical laboratory of 3,4 by 3,7 M had been built. Only one fourth of this confined space, a work table with two seats, was avaible for the chlorine titrations so that every corner on the table and against the wall had to be used to accomodate the necessary bottles, burettes, pipettes, porcelain dishes, etc., which must be within easy reach of the analyst. The table placed lengthwise of the ship to minimize troubles due to rocking was divided in two parts by a wash basin on each side of which there was a stand holding the burette and clamps for the pipettes. At the foreside the table was provided with a rim to prevent the glass ware from slipping off a measure which in the calm tropical seas proved entirely sufficient to preclude interruption of our work by unfavourable wheather. To the right of each seat were racks with bottles containing the solutions of silver nitrate, potassium chromate, and potassium dichromate-sulfuric acid, while on the left hand side the space had been reserved for the tubes with normal seawater and the bottles with water samples to be examined. The space under the table was used for the storage of glass ware.

A foto of the interior of the laboratory is shown in Plate II fig. 8.

Apparatus. The actual titration was carried out by means of the Knudsen automatic burette which consists of a thin tube graded in double c.c. (one double c.c. = 2 cm^3) and ending in a bulb of about 17 double c.c. At its upper end this bulb is provided with a two way stop cock which in the position indicated in fig. 1B connects the burette to an overflow reservoir R. When a titration is finished the burette is refilled from a stock bottle by opening the stop cock C; next C is closed, the stop cock S turned the other way and the burette is ready for another titration. The scale on the tube of the burette which ranges from 17 to 22 double c.c. is subdivided in 0,01 double c.c. so that readings can be made to 0,001 double c.c. or 0.002 cm^3.

We have of course made a grateful use of the numerous innovations introduced by the Meteor such as the fine black scale divisions all around the tube in order to avoid parallax, the narrow outlet, and the long handle of the cock; these were found valuable improvements in practice.

The calibration of the burettes was carried out with the utmost care at the „Physikalisch Technische Reichsanstalt" in Berlin the volume being checked at five points on the scale viz. at 17.1, 18.0, 19.0, 19.4, and 20.0 double c.c. In each case the reading was made 5 minutes after opening the cock a period which approximately coincides with the average duration of a titration. The deviations were very small never amounting to more than 0,01 cm^3.

The quantity of seawater required for the titration was taken with a Knudsen automatic pipette (fig. 23A). An accurate calibration of this pipette could be dispensed with since the same pipette was employed when taken a sample of the seawater under examination and when taking a sample of the normal seawater used for the calibration of the silver nitrate solution. A small error in the volume of the pipette is then automatically compensated by a corresponding error in the calibration of the silver nitrate solution.

To clean the instruments the pipettes were kept overnight in a solution of dichromate-sulfuric acid, whereas the burettes were cleaned in a similar way every 3 or 4 days when the stock bottles were filled with a fresh silver nitrate

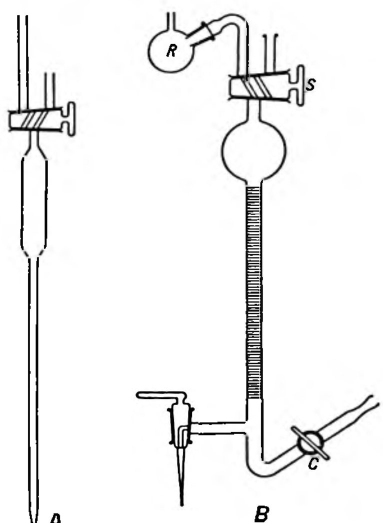

Fig. 23. A. Knudsen's automatic pipette.
B. Knudsen's automatic burette.

solution. In the tropics the glycerine which had been recommended for lubrication often led to sticking of the cocks a trouble which was mended by using small quantities of vaseline instead.

Reagents. The silver nitrate (chemically pure Ph. G. VI) was obtained from the „Deutsche Gold- und Silber- Scheideanstalt" at Frankfort on the Main. Before the expedition started it had been stored in 300 brown wide-necked bottles each containing 185.5 gr. silver nitrate a quantity sufficient to prepare 5 litres of a solution of the desired strength. The stops of these bottles were provided with Brolon capsules (Heyden) which proved a good sealing against moisture in the tropics.

For the calibration of the silver nitrate solution the so called „normal seawater" was used the chlorine content of which (19,368 per thousand in our case) had been accurately determined at the Hydrographical Laboratory in Copenhagen. This normal water is kept in sealed glass tubes of which we took 400 on board; more than 300 were used.

The titration. The water samples when brought on deck in the reversing water bottles (See Chapter I § 3) were immediately transferred to dark green, numbered bottles of about 180 cm^3 content, and provided with patent stoppers. To avoid as far as possible errors which may be caused by evaporation the chlorine titration was always carried out the same day.

With a Knudsen automatic pipette 15 cm^3 of the seawater was measured in a porcelain dish 15 cm in diameter to which 6 drops of a 10% potassium dichromate solution were added. It is of importance always to use the same amount since the end point of the titration is dependent on the concentration of the indicator. From the solubility products for silver chromate and silver chloride van Urk [1]) has calculated between what limits the indicator concentration may vary if no excessive errors are to be made. If the concentration is greater than 0,015 Mole per litre the end point of the titration is reached too soon, and with concentrations less than this value the amount of silver nitrate used becomes too large. It is therefore essential that the concentration of the indicator should be in the neighbourhood of this value. On the other hand it should also be taken into account that when the concentration is high the change of colour from yellow to red is not so sharp. The 6 drops of a 10% solution which we used in 15 cm^3 of seawater correspond to a concentration of 0.0021 Mole/Litre. From this value it may be computed that the amount of silvernitrate solution used in the titration will on the average be 0.008 cm^3 too high. Since, however, in titrating the normal seawater the same indicator concentration was used this error which is in itself extremely slight will be completely eliminated.

The most difficult point in the titration is the accurate observation of the end point which is marked by a change of colour from yellow to red. This end point is influenced both by the amount of stirring and by the rate of flow of the silver nitrate solution while the conditions of illumination are also of some importance. By the use of the normal water method errors due to these sources will for the greater part be eliminated. To keep the illumination as constant as possible a frosted glass window of 20 to 20 cm was fixed in the wall at the back of the tables where the titrations were carried out.

The reading of the burettes were made by the lowest point of the meniscus errors due to light reflection being avoided by placing a piece of frosted glass behind the tube. Special precautions to prevent errors due to the movement of the ship could be dispensed with, the wheather conditions being generally favourable and the sea correspondingly calm.

Most accurate results can only be obtained after considerable experience by which a uniform method of working has been acquired. When we arrived in the Netherlands East Indies, the actual scene of our operations, two of the four sailors available had already progressed so far that serious errors no longer occurred.

Moreover each titration was carried out in duplicate by different analysts without knowledge of each others results. Each worked with his own stock bottle of silvernitrate solution which were never exactly of the same concentration so that their titrations were not directly comparable either.

The calculation of the chlorine content.

As mentioned earlier the concentration of the silver nitrate solution was determined by means of normal seawater with a chlorine content of 19,368 per thousand. The difference between this value and the burette reading is the so called α correction. Given the α correction and the reading

[1]) H. W. v. Urk. Z. Anal. Chem. 67, 281, 1925.

of the burette when titrating a water sample we may from Knudsen's „Hydrographical Tables" find the k correction, which added to the burette reading will yield the chlorine content of the sample.

For instance if 19.425 double c.c. are used for the normal sample the α correction will be 19,368 — 19,425 = 0,057. With this value and a burette reading (after correction for the burette error) of 19.46 for the water sample we find a k correction of — 0,06 so that the actual chlorine content of the sample is 19,46 — 0,06 = 19,40‰.

Accuracy

All together 14 328 chlorine titrations were carried out in the course of the expedition. The observations were checked by plotting the temperature against the salinity for each station a method also adopted by the Meteor. Generally we obtain smooth curves but in 279 cases the salinity observations were found to deviate from these curves to such an extent that they were set aside as erroneous. From the remaining set the deviations from the average were computed for each pair of titrations and the frequencies of these deviations for various groups of stations and for all stations together are recorded in table 28. The standard errors of a single titration entered in the last row have been calculated by formula (12) of chapter I § 4 of this volume.

TABLE 28. Frequencies of deviations from the average for the salinity determinations.

Stations	25—75	75—125	125—175	175—225	225—275	275—332	332—382	25—382
Deviation in 0,01‰	Frequencies							
0,0	535	887	862	1077	879	800	857	5897
0,5	735	801	805	927	1045	890	848	6051
1,0	398	195	220	234	277	247	150	1721
1,5	33	7	8	42	78	57	51	276
2,0	23	—	1	4	31	20	2	81
2,5	8	1	—	1	5	5	—	20
3,0	1	—	—	1	—	—	—	2
3,5	—	—	—	—	1	—	—	1
Total	1733	1891	1896	2286	2316	2019	1908	14049
Standard error in 0.01‰	0,96	0,65	0,68	0,72	0,88	0,84	0,71	0,78

We see that the accuracy of our titration during the voyage to the Indies (St. 0—25) is slightly less than that obtained during the actual expedition. Among the different groups of stations the error is not entirely constant but the variations are not excessive; the overal error of 0,0078‰ fr a single titration is quite satisfactory.

Unfortunately it is not possible precisely to compare our results with those obtained on board Meteor owing to the fact that for the larger deviations no detailed frequencies have been given in the Meteor Reports [1]); in more than 7% of the cases the deviations were greater than 0,02‰ but the exact frequencies have not been specified and a correct calculation of the standard error is consequently impossible. If, however, we assign the value 0,02‰ to all the deviations that were actually greater the error computed will certainly be too low; doing so we obtain a value of 0,0115‰ for the chlorinity since the frequencies given by the Meteor refer to this quantity. The corresponding error in the salinity will be 0,021‰ which is considerably greater then the value computed from our own observations. Presumably the Meteor observations have been less accurate owing to the bad weather conditions prevailing in the Atlantic.

It is perhaps worth noting that in both cases (Meteor and Snellius) the frequencies do not at all follow a normal error curve of the form

$$f(x)dx = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{x^2}{2\sigma^2}} dx$$

[1]) Meteor Reports Vol. IV. Part. I. p. 283.

This may be seen from fig. 2 and 3 where the logarithm of the frequency has been plotted against the square of the deviation.

In drawing this plot the frequencies of the deviations other than zero were divided by 2 since

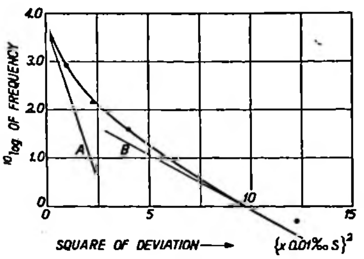

Fig. 24. Snellius.

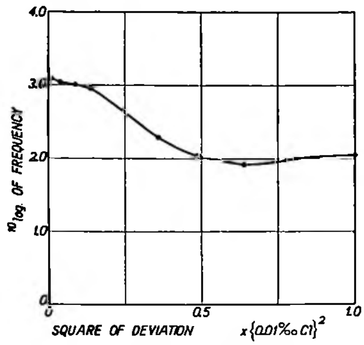

Fig. 25. Meteor.

Logarithm of the frequency plotted against the square of the deviation from the average for pairs of titrations. In the case of the Snellius the salinity has been used; for the Meteor the chlorinity titrations were used.

one half must be considered to have been negative the other half being positive. In figs. 24 and 25 the normal error curve would be represented by a straight line but the actual observation are seen to deviate markedly from such a straight course, a fact which may be explained by a variable accuracy. In that case it is clear that to obtain a correct representation of our observations both at the peak and in the tail of the frequency curve the standard error must have varied at least between the limits indicated by the two straight lines A and B, that is between 0,0046 and 0,0103$^0/_{00}$ respectively. In the case of the Meteor the curve is less regular but here too large variations are indicated. Exactly similar conditions were oberved for our oxygen titrations (see fig. 26) the limits being in this case 0,015 and 0,045 cm^3 0_2/L.

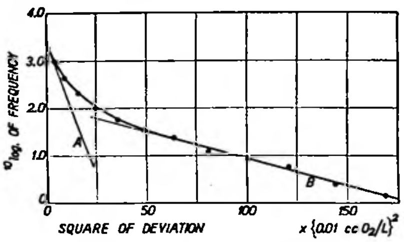

Fig. 26. Logarithm of the frequency plotted against the square of the deviation from the average for our oxygen titrations.

Whether the accuracy actually varied to such an extent can only be settled by an elaborate analysis of our material which lies outside the scope of these reports. On the other hand, though theoretical considerations lead us to expect the normal error law to occur frequently, it is not a law which has been universally established. The results illustrated by figs. 24, 25 and 26 may therefore also be interpreted as indicating that the normal error curve does not apply to chemical titrations.

An independent check on the accuracy of our titrations is afforded by the analysis carried out by T. G. Thomson and collaborators [2]) on samples collected and send to him during the voyage to the Indies. The results of their titrations carried out by Vollhard's method with weighed quantities of seawater have been entered in table 29 together with our own data. The average difference is + 0.005$^0/_{00}$ the standard deviation from this difference being 0.013$^0/_{00}$. The mutual agreement is quite satisfactory especially if we remember that during the outward voyage the analysts had not yet fully mastered the technique of the titrations.

Another series of samples taken during the expedition were send in well sealed bottles to Ir. Liebert at den Helder for titration in his laboratory. His observations, however, show a considerable deviation from ours the average difference for 23 samples being 0.042$^0/_{00}$ in the salinity. Subsequently in some of these cases a second titration was made by one his assistents viz. Mr. Timmermans whose observations are in much closer agreement with those made on board. The average difference for 6 samples was now 0.012$^0/_{00}$. It must be concluded that some serious systematic error must

[1]) T. G. Thompson, W. R. Johnston and H. E. Wirth. Jl. du Conseil VI, 1931.

TABLE 29. The observations of T. G. Thompson and collaborators in comparison with our own data.

Position	Depth in M	Chlorine content in ‰		
		Thompson	Snellius	Difference
37° 13′ N / 6° 55′ E	0	20,45	20,48	+ 0,03
	900	21,28	21,29	+ 0,01
36° — 38′ N / 12° — 57′ E	0	20,71	20,72	+ 0,01
	900	21,44	21,44	0,00
35° 6′ N / 17° 24′ E	0	21,14	21,15	+ 0,01
	900	21,44	21,44	0,00
33° 59′ N / 21° 15′ E	0	21,22	21,25	+ 0,03
	900	21,43	21,41	— 0,02
33° 6′ N / 21° 15′ E	0	21,41	21,40	— 0,01
22° 57′ N / 37° 12′ E	0	22,07	22,08	+ 0,01
	900	22,47	22,46	— 0,01
7° 39′ N / 37° 43′ E	1500	19,36	19,37	+ 0,01
3° 48′ N / 63° 48′ E	0	19,21	19,22	+ 0,01
	500	19,44	19,44	0,00
0° 4′ N / 79° 43′ E	0	19,54	19,53	— 0,01
	500	19,38	19,39	+ 0,01
1° 6′ S / 94° 56′ E	0	19,26	19,25	— 0,01
	4000	19,19	19,21	+ 0,02
	Average difference =			+ 0,005
	Standard deviation =			0,013

have been made in the first series of observations; they do not provide a satisfactory check on our data and we will not record them in further detail.

§ 2. THE DETERMINATION OF THE OXYGEN CONTENT OF THE SEAWATER

a. **Inventary**

For the oxygen determinations we had on board.

8 burettes from 0 to 50 cm^3
16 pipettes of 1 cm^3
8 pipettes of 3 cm^3
9 pipettes of 5 cm^3
8 Knudsen automatic pipettes
8 volumetric flasks of 500 cm^3
200 bottles of 200 to 300 cm^3 capacity with glass stoppers
together with a stock of erlemeyer flasks and bottles in different sizes.

The reagents were
15 KG manganous chloride puriss. cryst.
9 KG sodium hydroxide „Merck pur".
27 KG sodium thiosulfate puriss.
5 KG potassium iodide „Kahlbaum p.a."

1 KG potassium bromate p.a.
100 tubes potassium iodate „Fixanal"
150 KG hydrochloric acid.
1 KG amylum sol.
15 KG alcohol.

b. The determination of the oxygen content of the seawater

The determination of the „oxygen content" — that is the amount of oxygen in cm^3 at 0° C and 760 mm pressure dissolved in 1 litre seawater — is carried out by the method of Winkler [1]) dating from 1888. The simple analysis yields results which differ only slightly from those obtained by the standard gasometric methods.

It is based on the ready oxidation in alkaline milieu of manganous hydroxide precipitate to manganic hydroxide by which process the oxygen dissolved is completely used up. Subsequently upon the addition of concentrated hydrochloric acid manganic chloride is formed which oxidizes previously added potassium iodide liberating an equivalent amount of iodine which can be titrated in the usual way with sodium thiosulfate.

The analysts

The oxygen titrations were carried out by the wife of the leader of the expedition Mrs. van Riel-Verloop whilst duplicate determinations were made by the second class Seaman P. J. Louws.

The laboratory arrangement

One half of a table placed lengthwise of the ship in the centre of the laboratory was used for the oxygen titrations. (Plate II Fig. 9) This table was divided in two parts by a wash basin on both sides of which there was room for one analyst. In the centre of each half a burette support had been fixed; on the left racks were arranged with bottles containing solutions of manganous chloride, sodium hydroxide-potassium iodide, concentrated hydrochloric acid, and soluble amylum used as indicator, while on the right space had been reserved for a stock bottle with 0,02 normal thiosulfate solution.

Apparatus and reagents

For the titration a known volume of seawater must be used. This was measured off in bottles of 250—300 cm^3 capacity which had been carefully calibrated beforehand. They were provided with glass stoppers slantingly ground off at their lower end so as to prevent the inclusion of air bubbles when closing the bottle. Apart from one hundred bottles of this type we also had on board about 100 bottles of 180 cm^3 which were used particularly when besides the determination of oxygen content and chlorinity other analysis had to be carried out.

After filling these bottles with seawater (as described in more detail below) the solutions of manganous chloride and sodium hydroxide-potassium iodide were added by means of pipettes which were provided with two horizontal lines one above and one below the bulb the volume between them being accurately 1 cm^3. The content of the pipettes was allowed to flow off down to the lower line and in this way it was rendered possible to deposit the solutions close to the bottom of the bottle which prevented the precipitate from spreading throughout the liquid and from absorbing some oxygen from the air.

The burettes used in the titration had a scale ranging from 0—50 cm^3 the fine black lines of the scale being drawn all around the tube so as to avoid errors of parallax.

For the preparation of the various solutions we used the chemicals mentioned in the inventary at the beginning of this section. It should be specially checked that the solutions of manganous chloride and of sodium hydroxide-potassium iodide do not contain any nitrates as this compound disturbs the oxygen determinations. The exact concentration of the 0,02 normal thiosulfate solutions was calibrated by means of weighed quantities of potassium iodate which had been taken along in the form of so called „fixanal cartridges" prepared by E. de Haen. (Seelze Hamburg).

The determination

As soon as the reversing water bottles — with which the water samples are taken from the

[1]) L. W. Winkler. Ber. Deutsche Chem. Ges. 21, 2843, 1888.

depths of the sea (see this volume Chapter I § 3) — were brought on deck two of the glass bottles were filled from them by means of a glass tube 20 cm in length fixed to the tap of the reversing water bottle by a piece of rubber tubing. This glass tube after being rinsed out by letting a small quantity of seawater flow away was inserted in the bottle until its lower end touched the bottom and the bottle was then filled slowly so that no whirls in the liquid occurred. After some water had been spilt over the edge the stopper was inserted care being taken that no air bubbles were included. These various precautions were necessary to prevent dissolution of oxygen from the air while filling the bottle. In fig. 3 of Plate I a bottle is just being filled.

After reopening the bottle in the laboratory 1 cm^3 of a 20% manganous chloride solution and 1 cm^3 of a solution containing 10% sodium hydroxide and 5% potassium iodide were added. As a consequence 2 cm^3 of seawater would flow away so that the water sample actually investigated is 2 cm^3 less than the volume of the bottle, a fact which must be taken into account in carrying out the calculations.

Next the stopper was replaced and the bottle thoroughly shaken so that the manganous hydroxide precipitate was uniformly distributed through the liquid. All the oxygen dissolved is now absorbed transforming an equivalent amount of the lightly coloured manganous hydroxide into the brownish manganic compound.

Subsequently the bottle was left standing until the precipitate had again settled down whereupon 3 cm^3 of concentrated hydrochloric acid were added; thereby the precipitate is dissolved the liquid assuming a yellow tint owing to the liberation of iodine. The content of the bottle was now transferred to a 500 cm^3 Erlemeyer flask and the iodine titrated with 0,02 normal thiosulfate solution, 1 cm^3 of soluble amylum solution being added as indicator.

The normality of the thiosulfate solution which was checked twice weekly receded only slightly owing to the addition of 0,5% sodium carbonate. The accuracy of the fixanal cartridges was checked prior to the expeditions departure and once again after the activities on board Snellius had been concluded. Changes which might possibly result from dissociation of the potassium iodate could not be observed. Even some cartridges which were kept in the tropics for 4 years after the return of the expedition gave solutions differing by less than 5×10^{-5} normal from the required concentration.

Of all water samples investigated duplicate determinations were made by two analysts which had no knowledge of each others results.

The calculation

The oxygen content is usually expressed in cm^3 of oxygen (at 0 °C and 760 mm pressure) dissolved in 1 litre of seawater. It is easily computed that 1 cm^3 of a 1 normal thiosulfate solution will correspond to 0,25 milli mole of oxygen, that is to 5,596 cm^3 at 0 °C and 760 mm. Consequently if the capacity of the bottle is x cm^3, the amount y cm^3 of a thiosulfate solution of normality z being used in the titration, then the oxygen content will be given by

$$0 = \frac{5596 \, . \, y \, . \, z}{(x - 2)} \text{ cm}^3/\text{litre}.$$

It is sometimes more convenient to express the oxygen content in percentages of the saturation concentration, that is of the oxygen content of seawater of the same temperature and salinity when in equilibrium with air at a pressure of one atmosfere. The dependence of the saturation values on temperature and salinity has been investigated by Fox [1]) and he has composed extensive tables giving the oxygen content of air saturated seawater as a function of these two factors.

As we have stated above two independent titrations were carried out for each water sample. To investigate the accuracy obtained the deviations from the average were computed for each pair and the frequencies of these deviations for various groups of stations have been collected in table 30.

In the last line of the table the standard errors of a single titration computed according to the formula given by Hamaker in Chapter I § 4 of this volume

$$s = \sqrt{\frac{\Sigma d^2}{N}}, \quad N = \text{number of pairs}$$

[1]) C. J. J. Fox. Publ. de Circ. 41. 1907.

have been entered. We see that on the outward voyage (St. 0—25) and the first stages of our work in the Indian Archipelago (St. 25—75) the accuracy was comparatively poor no doubt owing to a lack of routine of the analysts. From station 75 onwards the errors are practically constant and the accuracy is quite satisfactory. It should be noted that the error in the average of two titrations is $\sqrt{2}$ times smaller than the error given in table 3 for a single titration.

TABLE 30. Frequencies of deviations from the average for pairs of oxygen titrations.

Group of stations	0—25	25—75	75—125	125—175	175—225	225—275	275—332	332—382	0—382
Deviation in 0,01 cm^3 per litre	Frequencies								
0	26	236	255	413	397	500	323	325	2475
1	24	371	511	603	600	635	499	525	3768
2	16	252	237	278	287	272	246	318	1906
3	9	154	79	95	123	121	131	140	852
4	7	101	32	36	54	43	72	73	418
5	2	68	13	18	16	26	29	38	210
6	1	50	4	2	13	15	20	10	115
7	2	26	5	4	9	8	13	2	69
8	—	18	8	—	7	4	9	2	48
9	1	19	1	2	—	—	2	—	25
10	—	7	5	—	2	3	1	—	18
11	2	4	—	—	2	1	2	—	11
12	—	5	—	—	—	—	—	—	5
13	—	3	—	—	—	—	—	—	3
14	—	1	—	—	—	—	—	—	1
15	2	2	—	—	—	—	—	—	4
16	—	1	—	—	—	—	—	—	1
17	1	—	—	—	—	—	—	—	1
Total	93	1318	1150	1451	1510	1628	1347	1433	9930
Standard error in 0.01 cm^3 O_2/L	6,9	4,8	2,8	2,4	2,8	2,7	3,2	2,8	3,15

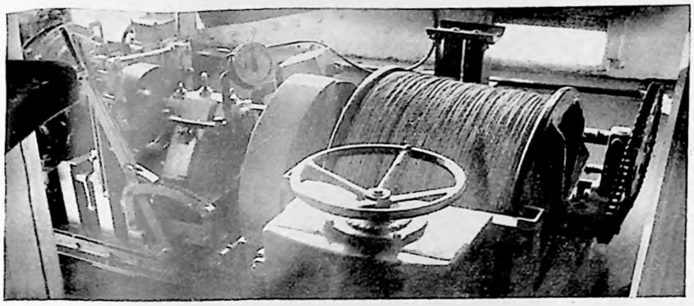

Fig. 1. The serial winch.

Fig. 3. Racks with reversing water bottles on deck. A bottle for oxygen titrations is just being filled.

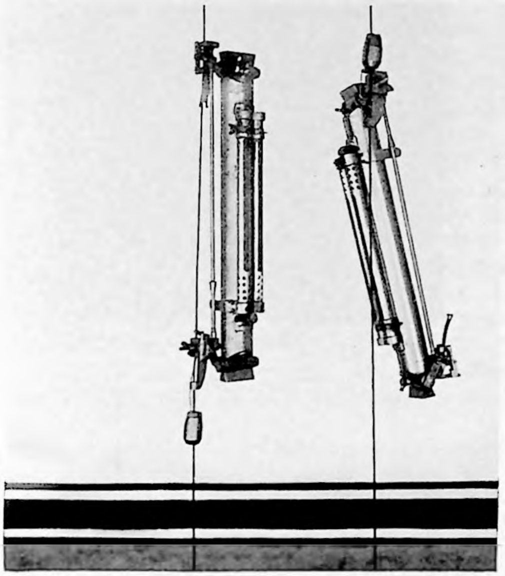

Fig. 2. Nansen reversing water bottles.
left: lowered, open; right: hauled in, closed.

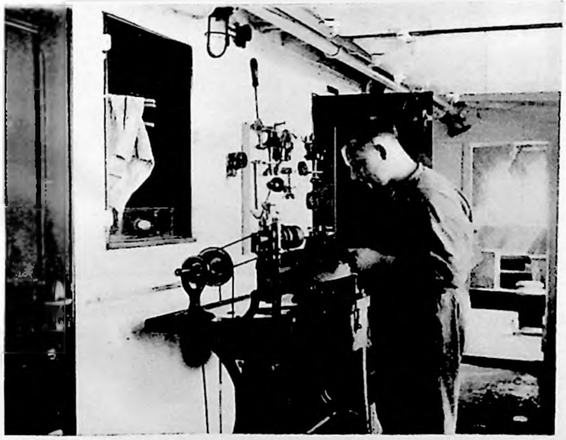

Fig. 4. The Instrumentmaker at his lathe.

Fig. 5. A bottom water bottle and a Nansen reversing water bottle used together for bottom observations.

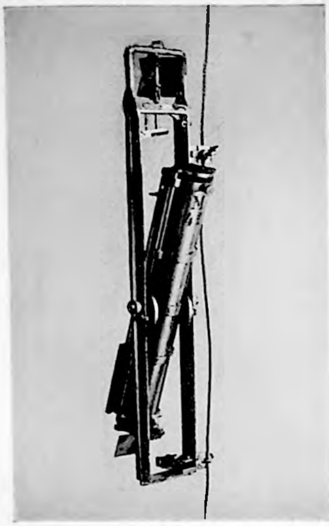

Fig. 6. Bottom water bottle (Marx & Berndt).

Fig. 7. 'Ekman' repeating current-meter.

Fig. 9. The chemical laboratory; table arranged for oxygen titrations.

Fig. 8. The chemical laboratory: table arranged for chlorine titrations.

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